PENJAJAWOC STREAM ANALYSIS AND INTERPRETATION

(FINAL REPORT)

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PARISH geomorphic

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1.0 INTRODUCTION

As a result of urban development and growth pressures impinging on the Penjajawoc Stream Watershed, the City of Bangor, in collaboration with the MDEP, has identified the need to develop a watershed management plan that identifies protection and restoration goals for the stream. As part of this watershed management plan, a fluvial geomorphological study was conducted in order to provide a comprehensive understanding of channel processes and the function of Penjajawoc Stream and its tributaries.

As summarized in the Existing Conditions Report (September 2005), six reaches were proposed for a detailed geomorphological investigation. The location of the detailed sites was determined utilizing three methods. The first method involved choosing detailed sites which provided representative coverage of the watershed, both from a spatial and morphologic perspective. The second method, selected sites on the basis of their relative sensitivity according to the RGA and RSAT results (provided in the Existing Condition Report). The final component was to choose a site with the potential for use as reference reaches (i.e., reaches potentially used during development of restoration plans).

Reach PST5-4 was chosen to provide conditions representative of the headwaters of Penjajawoc Stream, while reaches PS-4 and PS-6/PS-7 were meant to provide representative data over the entire range of geomorphic stability rankings on the main branch of the stream. Reach PST2-3 provided insight into conditions along a particularly sensitive and geomorphologically active section of the system while reach PST1-2 served as a 'reference reach' that was indicative of a relatively healthy and stable channel. This being said, it was acknowledged that given local land use conditions, identifying a true "reference" site was not likely. Finally, PS-2 was chosen to represent conditions at the downstream extent of the watershed.

2.0 MONITORING

In addition to collecting data of existing conditions, erosion pins and control cross sections were installed throughout the watershed that enabled an evaluation of rates of channel change (e.g., bank erosion, bed scour and fill). Typically, two to five erosion pins were installed at varying locations along banks at each field site. The pins were placed both in channel bends (where bank erosion was expected to occur) and in straight sections that are usually more stable. The pins have been revisited once since installation, this followed several flow events. As such, installation occurred between August 22nd, 2005 and August 25th, 2005, whereas the sites were revisited on November 4th, 2005. Erosion pin data along with their associated reach names is provided in **Table 1**.

Erosion pin results indicate a fairly low degree of channel migration during this period. With the exception of the west bank pin installed at the upstream end of Reach PS-2, where an approximate loss of 0.50 ft/yr was established; in addition, the west bank pins installed upstream of the monitoring cross section PS-4 established a loss of 0.73 ft/yr and 0.39 ft/yr respectively. Generally, the majority of erosion rates measured to date are typical for a dynamic system such as the Penjajawoc Stream, where the rate of erosion ranged from 0.07 ft/yr to 0.28 ft/yr (see **Table 1**). These values however do not provide a robust estimate of long term trends due to the limited period of monitoring to date. Therefore, it is recommended that monitoring be continued to better clarify trends of erosion and deposition.

Repeated surveys were conducted at six monitoring cross sections to document processes of deposition, downcutting and channel widening. Cross sections were generally located in the vicinity of erosion pins in order to provide comparison data. Generally, these sections were located on riffles as they are the most stable and persistent channel features. Control cross-section locations are marked in red text on **Figure 1** and the explanation of the terms from the legend can be found in **Appendix E**. Initial set-up of the control cross sections occurred between August 22nd, 2005 and August 25th, 2005; re-measuring of the sections was completed on November 4th, 2005. Qualitative changes in cross-sectional form over the period of measurement can be assessed from the series of graphs depicted in **Appendix A**.

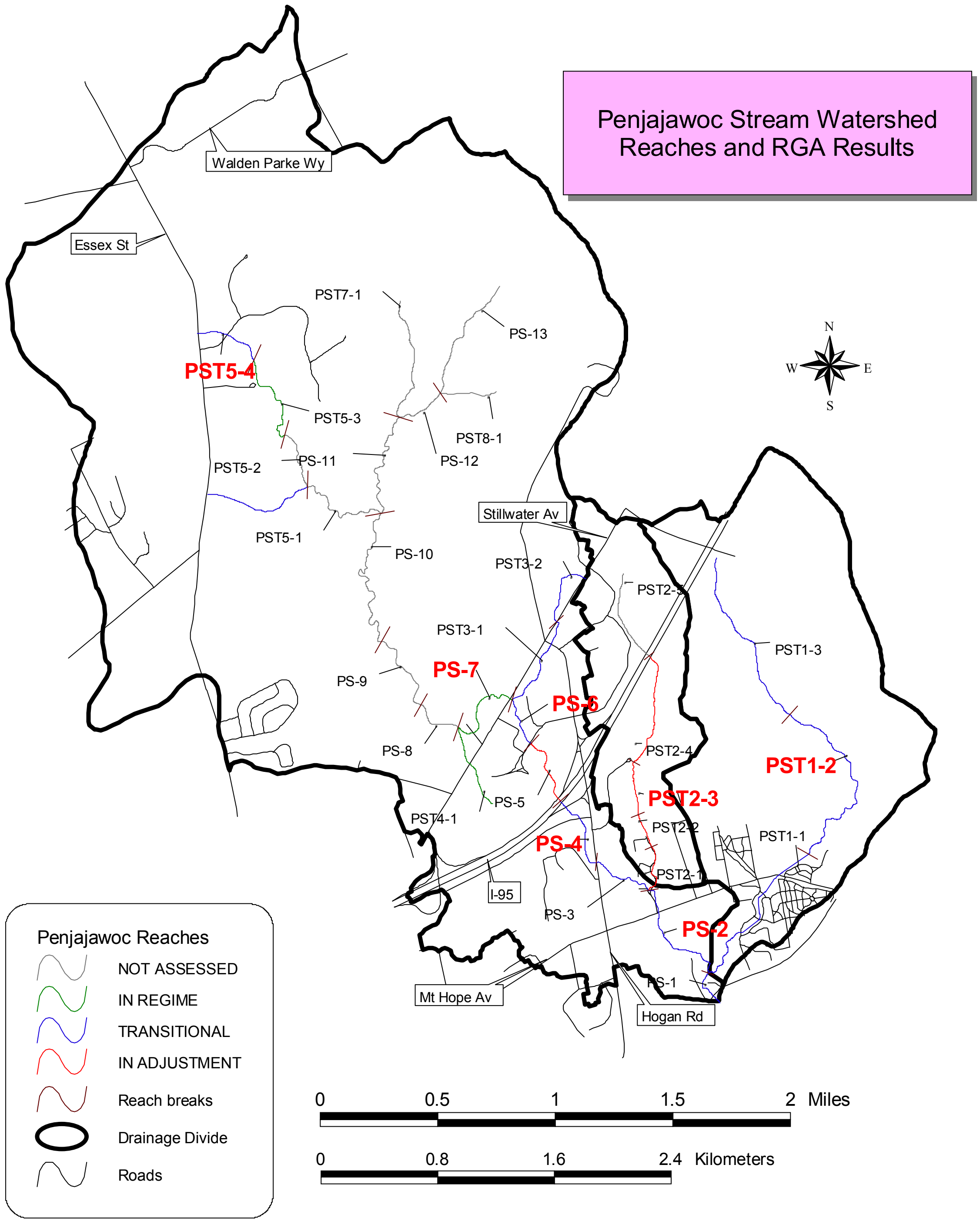

Figure 1. Location map with identified reaches.

From the baseline monitoring data already collected, the rates of migration and potential variation in channel cross-section can be assessed; there are two geomorphological triggers:

- qualitative visual observations of change in the stream's physical condition including changes in channel geometry, channel and bank substrate, quantities of wood debris and riparian vegetation; and
- percent change in cross-sectional area, as there are natural seasonal and event driven changes in cross-sectional area and cross-sectional form

Generally, results of monitoring data indicate that Penjajawoc Stream and tributaries has experienced minimal change in cross-sectional shape and area (see **Table 2**). Most control cross sections display only minor adjustments which are likely due to a shift or movement of large particles during the recent high flow events which occurred during the period of monitoring. According to the NOAA website, the month of September (2005) was fairly normal with regards to rain events, with no large storm events noted; however, October 2005 was an exceptionally rainy month, breaking the previous monthly rainfall record of 8.92 in. set in 2003. As a result, the total precipitation for October 2005 was 13.32 in. NOAA linked the heavy rain for the month of October to the active tropical storm season of 2005. One significant storm to note occurred on October 8^{th} and 9^{th}, where a total of 6.66 in. of precipitation was recorded.

The percent change for monitoring cross section PS-2 was minimal, where only -0.19% change was recorded. A minor shift in bed material was noted in **Figure A** (in **Appendix A**) where sediment accumulation on the top and toe of the east bank, and degradation at the toe of the west bank was prominent. In general, the migration trend of cross section PS-2 is towards the west; however, it should be documented the change in cross sectional area may be attributed to human error due to fact the site was monitored by two separate teams. It is important to note that there was no change in erosion pin exposure for EP-2 located within the monitoring cross section.

Changes in cross sectional area for PS-4 resulted in a 0.76% loss, where only notable changes on the bed were observed. Bed aggradation was apparent, in addition to minor sediment accumulation on the banks. Overall, there were no major shifts within the monitoring cross section; however, it should be noted that the cross section was located within a straight section of the watercourse where generally minimal movement is anticipated.

Table 1. Penjajawoc Stream Erosion Pin Assessment

Erosion	Location					Amount Exposed (in)		Net Change	Erosion Rate
Pin #	**REACH**	X-S	Left	Right	Comment	24-Aug-05	04-Nov-05	(in +/-)	(ft/yr)
EP-1	**PS2**		✓		Located at XS-3 in east bank at undercut	6.5	6.5	0.00	0.00
EP-2	**PS2**	✓		✓	Located at monitoring XS-4 in west bank	5.7	5.7	0.00	0.00
EP-3	**PS2**		✓		Located at XS-7 in east bank	4.2	4.3	-0.16	-0.07
EP-4	**PS2**			✓	Located at XS-7 in west bank	4.9	6.1	-1.18	-0.50
Pin #	**REACH**	X-S	Left	Right	Comment	22-Aug-05	04-Nov-05	(in +/-)	(ft/yr)
EP-1	**PS4**	✓		✓	Located at upstream of XS-1 at rip rap spillway	5.7	7.5	-1.77	-0.73
EP-2	**PS4**	✓		✓	Located at upstream of XS-1 at rip rap spillway	6.9	7.9	-0.94	-0.39
EP-3	**PS4**	✓	✓		Located downstream of XS-3 in east bank (near apple tree)	6.1	6.1	0.00	0.00
EP-4	**PS4**			✓	Located at XS-8 in west bank	4.8	5.5	-0.67	-0.28
EP-5	**PS4**		✓		Located at XS-9 in east bank	6.3	6.5	-0.20	-0.08
Pin #	**REACH**	X-S	Left	Right	Comment	25-Aug-05	04-Nov-05	(in +/-)	(ft/yr)
EP-1	**PS6/7**	✓		✓	Located at monitoring XS-6 in west bank	3.5	3.7	-0.20	-0.08
EP-2	**PS6/7**			✓	Located b/w XS-6 and 7 in west bank (at apex of meander)	3.9	3.7	0.20	0.08
EP-3	**PS6/7**		✓		Located 6.6 ft upstream of XS-7 in east bank	3.1	3.1	0.00	0.00
Erosion									
Pin #	**REACH**	X-S	Left	Right	Comment	25-Aug-05	04-Nov-05	(in +/-)	(ft/yr)
EP-1	**PST1-2**		✓		Located at XS-9 in east bank	4.0	4.7	-0.71	-0.30
EP-2	**PST1-2**			✓	Located 3.3 ft d/s of XS-9 on west bank	5.3	0.0	0.00	0.00
Erosion									
Pin #	**REACH**	X-S	Left	Right	Comment	23-Aug-05	04-Nov-05	(in +/-)	(ft/yr)
EP-1	**PST2-3**		✓		Located 3.3 ft u/s of monitoring XS-7 in east bank	3.7	4.1	-0.47	-0.20
EP-2	**PST2-3**	✓	✓		Located at monitoring XS-7 in east bank	2.4	2.6	-0.12	-0.05
Erosion									
Pin #	**REACH**	X-S	Left	Right	Comment	25-Aug-05	04-Nov-05	(in +/-)	(ft/yr)
EP-1	**PST5-4**		✓		Located 13.1 ft u/s of footbridge (XS-2) on east bank	5.2	5.3	-0.16	-0.07
EP-2	**PST5-4**			✓	Located u/s of XS-7 on west bank (birch tree)	6.7	6.1	0.59	0.25
EP-3	**PST5-4**	✓		✓	Located at monitoring XS-9 in west bank	5.5	4.7	0.79	0.34

(grey)	*Erosion*
(white)	*No Change*
(yellow)	*Deposition*

Results obtained from the cross sectional area assessment for cross section PS-6/PS-7 revealed a loss of 0.85%. Sediment accumulation was apparent in the center of the cross section, while evidence of aggradation and degradation of bank material was observed on the east bank. Based on the results obtained from the erosion pin assessment and the cross sectional area assessment indicate that no change in shape or form was observed along the west bank within this particular cross section.

Generally, cross section PST1-2 demonstrated the most change within the 3 month monitoring period, where a total cross sectional loss of 1.88% was recorded. Minor bank erosion was evident on the east bank, while the west bank experienced moderate sediment accumulation. As anticipated, the cross sectional shape of PST1-2 remained relatively consistent, where only a minor shift in material was noted. It is interesting to note that this site was deemed a "reference", yet experienced change. This is likely indicative of the condition of the local channels end response to large flows.

Cross section PST2-3 was the only monitoring site which demonstrated a minor increase of 0.72% in area. The increase in area can be attributed to the loss of a large boulder which was present during the August 2005 monitoring. The loss of the boulder was assumed to have been forced downstream during high flows. Besides the minor fluctuations in sediment aggradation and degradation on the banks, it should be noted that the vertical banks did not experience any major changes; which is also reflected in the erosion pin assessment where a net loss of 0.12 in was measured between the August 2005 and November 2005 field reconnaissance.

Finally, cross section PST5-4 experienced a loss of 0.42%, where only a slight change in channel form was noted. As such, sediment aggradation at the west bank (toe of the bank) was observed, which is also evident in **Table 1** where EP-3 had a net increase of 0.79 in. Additional changes within cross section PST5-4 can be seen on the east bank where minor sediment accumulation on the top of the bank has resulted from bank slumping.

Overall, results obtained from the cross sectional area assessment revealed channel conditions to be in a transitional state. Although only minor adjustment to channel form was observed over the monitoring period, areas of aggradation and degradation are still apparent when comparing the cross sectional form obtained in August and November 2005. As such, the results indicate that although high flows have occurred during the monitoring period, the channel at these locations has remained relatively stable.

Generally, a decrease in cross sectional area was apparent throughout all monitoring sites, where channel aggradation was the predominant geomorphic process acting within the channel (see **Table 2**). With the exception of Reach PST2-3 where channel degradation was prevalent, resulting in a percent increase of 0.72 ft^2 in cross sectional area. The resulting percent change was negligible, however with the continuation of monitoring, changes in channel form and trends of erosion and deposition will become more transparent. The results are fairly typical for urban watersheds, with channels experiencing adjustment. Most urban catchments dominant change is degradation and channel enlargement. These values suggest past disturbances has resulted in larger channels or a system with less energy.

Table 2. Change in cross sectional area and shape for monitoring sites

	CROSS SECTIONAL AREA (ft^2)		
	August 2005	*November 2005*	% Change
PS-2	77.49	76.89	-0.19
PS-4	178.83	173.48	-0.76
PS-6 - PS-7	42.29	40.88	-0.85
PST1-2	18.34	17.02	-1.88
PST2-3	30.06	30.93	0.72
PST5-4	24.48	24.07	-0.42

* Based on Total Cross Sectional Area

3.0 SEDIMENT TRANSPORT

A basin-scale assessment is vital to provide an understanding of the physical system, specifically the controls and modifying factors. Working at the basin-scale also facilitates an understanding of broad-level functions, sources of sediment and locations of production, transfer and deposition zones. This helps to provide a context for the findings of the reach assessment.

In order to determine the broad-level function occurring within Penjajawoc stream, a detailed assessment was completed. The detailed geomorphic assessments for this study included measurements of channel and bank characteristics and bankfull flow conditions. At each of the detailed sites, cross sections were measured at five to ten locations, including pools, riffles and transitional areas. At each cross-section, bankfull width and depth, entrenchment, as well as low flow dimensions were recorded. Substrate was sampled using a modified Wolman pebble count. Sub-pavement was also characterized at each cross-section. Bank assessment included measurements of height, angle, bank composition, *in-situ* shear strength, vegetation and rooting depth. These cross sections were placed over a minimum of two meander wavelengths. A level survey of the site extending upstream and downstream of the cross-section locations was also conducted. The survey included bankfull elevations, maximum pool depth, top and bottom of riffles and any obstruction to flow and provided measures of energy gradient, inter-pool gradient and riffle gradient. **Appendix B** provides a summary of measurements from the detailed sites.

Table 3 provides an at-a-glance summary of the bankfull characteristics and erosion thresholds for all the detailed sites. The bankfull characteristics and process observations from each detailed site are also provided to set the context for the thresholds. The collection of detailed field information allows for analyses to be performed based on critical shear stress and permissible velocities in order to identify critical discharges that represent erosion thresholds. As such, erosion thresholds determine the magnitude of flows required to potentially erode and transport sediment. When compared to bankfull discharge they provide an indication of channel stability (refer to **Appendix E** for detail descriptions of geomorphic terms). Streams continually adjust their dimensions to accommodate changes in their sediment transport and discharge regimes. As a result, thresholds of particle movement and transport will vary spatially and temporally as watercourses adjust to local variations in slope, bed material, discharge and modifying factors. Bankfull levels traditionally represent the level or stage of flow where the most amount of work is done in shaping and forming the channel. In natural areas, this level typically coincides with the top of bank or the limit before flow spills onto the floodplain. In urban areas, bankfull is typically lower on the banks due to local channel adjustment and disturbances. The critical values represent the level of flow where erosion or movement of channel material is initiated. This is frequently much below bankfull values. The critical flow can be applied to stormwater management facilities to ensure their release would not exacerbate existing channel erosion processes.

Table 3. Summary of Erosion Threshold Values.

	PS-2	PS-4	PS-6/PS-7	PST1-2	PST2-3	PST5-4
Average Bankfull Width (ft)	20.67	16.83	22.80	20.67	16.83	22.80
Average Bankfull Depth (ft)	12.07	8.53	9.58	12.07	8.53	9.58
Bankfull Gradient (%)	0.25	0.95	0.58	0.26	1.00	1.85
Bed Material D_{50} (in)	1.19	0.94	0.26	0.00*	0.81	0.85
Bed Material D_{84} (in)	3.60	4.43	1.97	0.00*	3.42	2.90
Manning's n at Bankfull	0.04	0.04	0.032	0.025	0.0280	0.030
Average Bankfull Velocity (ft/s)	9.24	15.94	15.95	7.56	21.18	17.74
Average Bankfull Discharge (ft^3/s)	2305.97	2289.86	3486.60	467.80	2034.23	955.73
Flow competence (ft/s) @ D_{50}	3.10	2.79	1.54	0.05	2.60	2.67
Flow competence (ft/s) @ D_{84}	5.17	5.69	3.92	0.20	5.05	4.69
Tractive Force at Bankfull (lb/ft^2)	1.85	5.08	3.47	0.64	4.98	4.91
Critical Shear (lb/ft^2) @ D_{50}	0.46	0.36	0.07	0.00*	0.31	0.33
Critical Shear (lb/ft^2) @ D_{84}	1.39	1.71	0.76	0.00*	1.32	1.12
Stream Power (W/m)	1573.26	6054.75	5608.45	319.16	5378.83	1537.36
Stream Power per Unit Width (W/m^2)	249.72	1180.26	806.97	50.66	1048.50	221.20
Critical Discharge (ft^3/s)	2.82	0.53	0.09	18.02	17.31	8.48
Critical Depth (ft)	1.30	0.47	0.20	0.66	0.69	0.75
Critical Velocity (ft/s)**	0.946	0.849	0.469	1.75	2.59	2.66

*A low value indicates very fine, silty materials

The calculations performed to determine critical discharge for bed materials were based on formulas for critical shear stress (Shields, modified by Miller et al., 1977) and permissible velocity (Komar, 1987). These methods are well suited for the coarse sediment channels found within the watershed. The erosion thresholds were based on the threshold for the D_{50} (median grain size), which is the general practice. Several clarifications are required with respect to the tables. The cross sections collected in the field were simplified to allow discharge to be readily back calculated. It should be noted that the critical depth calculated by the models is, more specifically, a maximum critical depth of the defined trapezoid. Where a critical velocity is shown, this critical value again pertains to the intitiation of particle movement, not the state flow that would be portrayed by a Froude # equal to or greater than one. Consequently, in some cases the critical depth of a site is greater than the average bankfull depth. In most cases the maximum bankfull depth would still prove larger than the maximum critical depth. The Manning's 'n' values provided in the tables were for bankfull conditions and were derived from Limerinos' (1970) equation using average bankfull depth and the D_{84} for a site.

Summarized in **Table 4** are the results obtained from the tractive force analysis (completed by Kleinschmidt Associates) for the monitoring cross sections for Penjajawoc Stream and tributaries. The goal of the analysis was to find the flow at which the D_{50} (median) particle is mobilized; i.e. the size of the particle at incipient motion. Due to the fact that the slope was estimated during bankfull conditions and the D_{50} was being mobilized at very low flows for the majority of the monitoring cross sections; another approach was utilized. As such, a more appropriate means to evaluate the tractive force was to asses the percent of the bed surface that is mobilized at the bankfull flow. **Appendix C** provides the results obtained from the tractive force modeling exercise for each monitoring cross section.

Generally, a slight variation among each reach was observed; however, the results reveal that most of the bed material is mobilized during bankfull conditions. As much as 95% of the bed material would be mobilized for one silt-dominated section, with as little as 37% being mobilized for a reach dominated by cobbles. Overall, the results acquired point to a system that is a very dynamic system, which has the potential to move a substantial amount of sediment. Although the situation may be exacerbated by the urbanization and related stormwater runoff, it appears that the watershed is comprised of erodible soils that would be readily mobilized.

Table 4. Summary of Tractive Force Analysis

Reach	Monitoring Cross Section	Bankfull Incipient Diameter* (in)	USCS Particle	% Bed Surface Materials Moved	Bankfull Slope	Bankfull Flow (cfs)	2-Year Flood (cfs)**
PS-2	4	0.88	coarse gravel	37%	0.0025	150	237
PS-4	1	1.60	coarse gravel	53%	0.0102	60	206
PS6-PS7	6	2.13	coarse gravel	81%	0.0059	140	193
PST1-2	7	0.61	fine gravel	95%	0.0026	30	78
PST2-3	7	3.96	cobbles	83%	0.0095	90	42
PST5-4	9	4.04	cobbles	87%	0.0184	100	57

* Particle size able to be moved by bankfull flow.
** Peak flow for 2-year flood determined using empirical relationships outlined in "Estimating the Magnitude of Peak Flows for Streams in Maine for Selected Recurrence Intervals", USGS, 1999. This approach relies solely on drainage area and may result in discrepancies of the 2-year flood discharge with respect to bankfull levels.

According to the Penobscot County soil survey, soils within the Penjajawoc Stream watershed were formed in either marine/lacustrine deposits or silty glacial till. The lower reaches of the stream are predominantly water deposits (marine/lacustrine) while the upper reaches tend toward glacial till with high amounts of silt/clay and some marine/lacustrine soils present. The glacial till in PST5-4, for instance, is a stony silty till (Howland series) and PST1-2 consists of mostly marine/lacustrine soils such as the Scantic series (silt/clay) and Biddeford, Scantic and Buxton series (stony silt loam). Although bank soils contain some larger substrates associated with till (e.g. cobbles, boulders), the high proportion of fines, especially in the lower reaches of the stream, mean that the soils are highly erodible if not stabilized with vegetation and are readily mobilized by streamflow. While urban runoff may be a large contributor of fine sediments to Penjajawoc Stream through stormwater input, the stormwater may be adding fines to a stream that already entrains a lot of fines through natural processes (e.g. channel meandering).

4.0 ANALYSIS OF CHANNEL PROCESSES

The analysis of field observations, detailed assessment, historic assessment and sediment transport modeling can provide general trends and relative quantification of potential sediment input, output and storage within the watershed.

Stream Data Analysis/Regime Analysis

The sediment transport modeling component of the study provides general patterns of sediment routing (i.e. sources, transfer areas and sinks) within the watershed. Information from the detailed sites provide the values necessary to characterize sediment transport through those reaches at bankfull conditions, which is expected to represent an event of long duration that would do the most cumulative work. If it is assumed that bankfull events between reaches occur at relatively similar intervals (return periods of 1.5 to 2 years) then comparison between reaches is also appropriate and the information provides insight into potential transport between zones of the watershed. Due to the distribution of detailed sites, this approach provides the potential relative contributions of sediment at the bankfull or effective discharge from most of the sub basins and at key locations along the main branch of the Penjajawoc Stream. Several modeling approaches are available to assess sediment load and the different components of the total load transported (i.e., suspended load, bed load). In this case, only potential bed load is modeled as it provides the most important component from a geomorphic perspective. The bed load also likely comprises the majority of the material transported through the system; this is supported by the coarse bed material found along almost all the reaches. Also, this material is the most important component with respect to the channel forming (e.g., riffles and bars).

There are numerous approaches to modeling bed load transport; all with their own strengths and weaknesses. Here a Einstein (1950) and Parker et al. (1982) approach are taken to model bed load. This simple method is based on the concept of stream power (work); that a portion of the potential energy to do work will be utilized to transport sediment. The simplicity of the method allows the model to be applied from the bankfull hydraulic values that were previously calculated (i.e. bankfull geometry, slope and velocity). As only relative contributions are needed from this modeling exercise, whether the model in fact provides accurate absolute values is not relevant. Also, the model results represent a potential bed load as the model assumes that the capacity of the channel is less then the available supply.

Table 5 presents the output of the sediment transport modelling exercise. For comparative purposes, bed load transport rates per unit width should be used as they eliminate any bias associated with channel dimensions. Three of the reaches (PST5-4, PST1-2 and PS-2) are in agreement with watershed scale conceptual models of sediment sources and sinks (**Figure 2**). PST5-4, a small headwater tributary, displays a relatively high sediment transport rate, indicating that is supplying sediments to the lower portions of the watershed. Middle reaches (PST1-2) display lower transport rates and are typically sites where sediment input is in equilibrium with sediment output. Downstream reaches such as PS2 have the lowest transport rates, and serve as sediment sinks with in the watershed. The other three detailed sites (PS4, PS6/PS7 and PS2-3) clearly have disproportionately high transport rates, which should be expected since their geomorphic or hydraulic properties don't agree with conceptual models.

Typically, low order streams (e.g. smaller, headwater channels) are characterized as having coarse sediments and steep gradients, resulting in a highly energetic environment. Given that sediment transport models are based on the ratio of stream power to particle size, PS6/PS7 has high transport rates due to its small bed substrates. Conversely, reaches PS4 and PS2-3 have the display the highest stream power (energy) of all the detailed sites. However, it should be noted that the values seen in **Table 5** represent potential transport capacities, not predicted transport rates. As such, their higher capacities indicate that they will be able to convey the sediment being delivered from the headwater areas; they do not necessarily indicate high erosion rates. This agrees with the conceptual model (**Figure 2**), where middle reaches convey sediment from the headwaters to the base of a watershed. Moreover, field observations indicate that the lower reaches and the headwaters are acting as they should; aggradation and widening are the dominant adjustments in the lower reaches and, with only a few exceptions, headwater areas are showing symptoms of degradation and/or channel widening.

Table 5. Bed load transport rates at bankfull conditions for the detailed site.

	Bed Load (lb/s)	Bankfull Channel Width (ft)	Flow Depth (ft)	Bed Load per unit width	Grain Size (D50) (in)
PS2	3.7	17.38	1.73	0.21	1.18
PS4	434.6	16.84	1.96	25.81	0.94
PS6-PS7	423.8	22.81	1.52	18.57	0.26
PST1-2	60.3	15.71	1.02	3.84	0.00
PST2-3	232.28	12.03	1.57	19.30	0.81
PST5-4	152.1	12.32	0.75	12.34	0.85

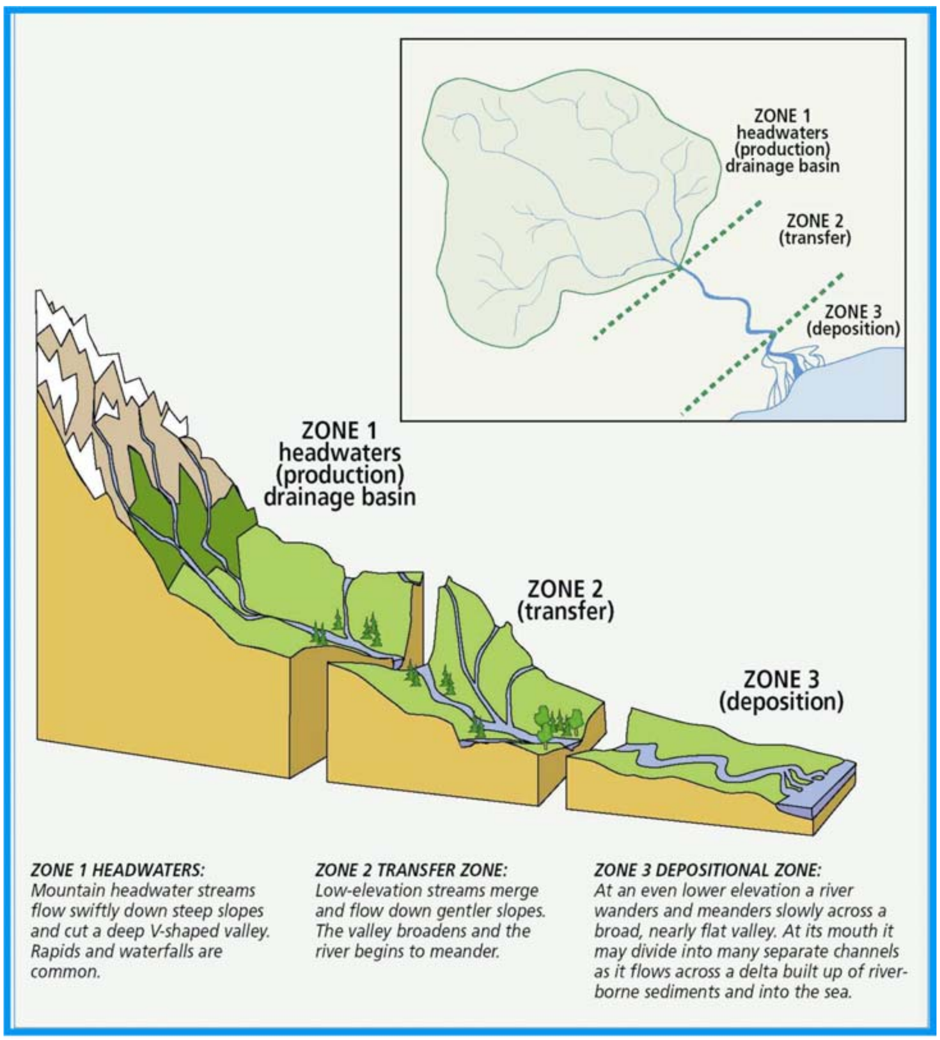

Figure 2. Idealized Fluvial System (Source: Miller 1990 (lower portion) and Schumm 1976 (upper portion))

Hydraulic Geometry

To link the observations of channel form, process and adjustments, several key concepts need to be presented. First, as mentioned previously, watersheds can be divided conceptually into zones of production, transfer, and deposition, from upstream to downstream dependent on dominant form and function **Figure 3** represents a model that theoretically may help predict future upstream or downstream changes in habitat and and stream morphology. A disturbed or unstable stream is in varying stages of disequilibrium along its length or profile. Headwater (production) zones are characterized by steep gradients, little in the way of alluvial storage and floodplain, and net loss or production of sediment which is transported to the downstream channels. Transfer zones are characterized by wide floodplain, moderate gradients and meandering patterns. The floodplains provide areas for temporary storage of sediment. Generally, there is no net gain in sediment within the system. Further downstream, the depositional zone is characterized by "flat" gradient, strong meandering pattern and net sediment storage. The geomorphic evidence presented here (observation of form and dominant processes) indicate that the Penjajawoc Stream catchment generally fits this conceptual model (see **Figure 3**).

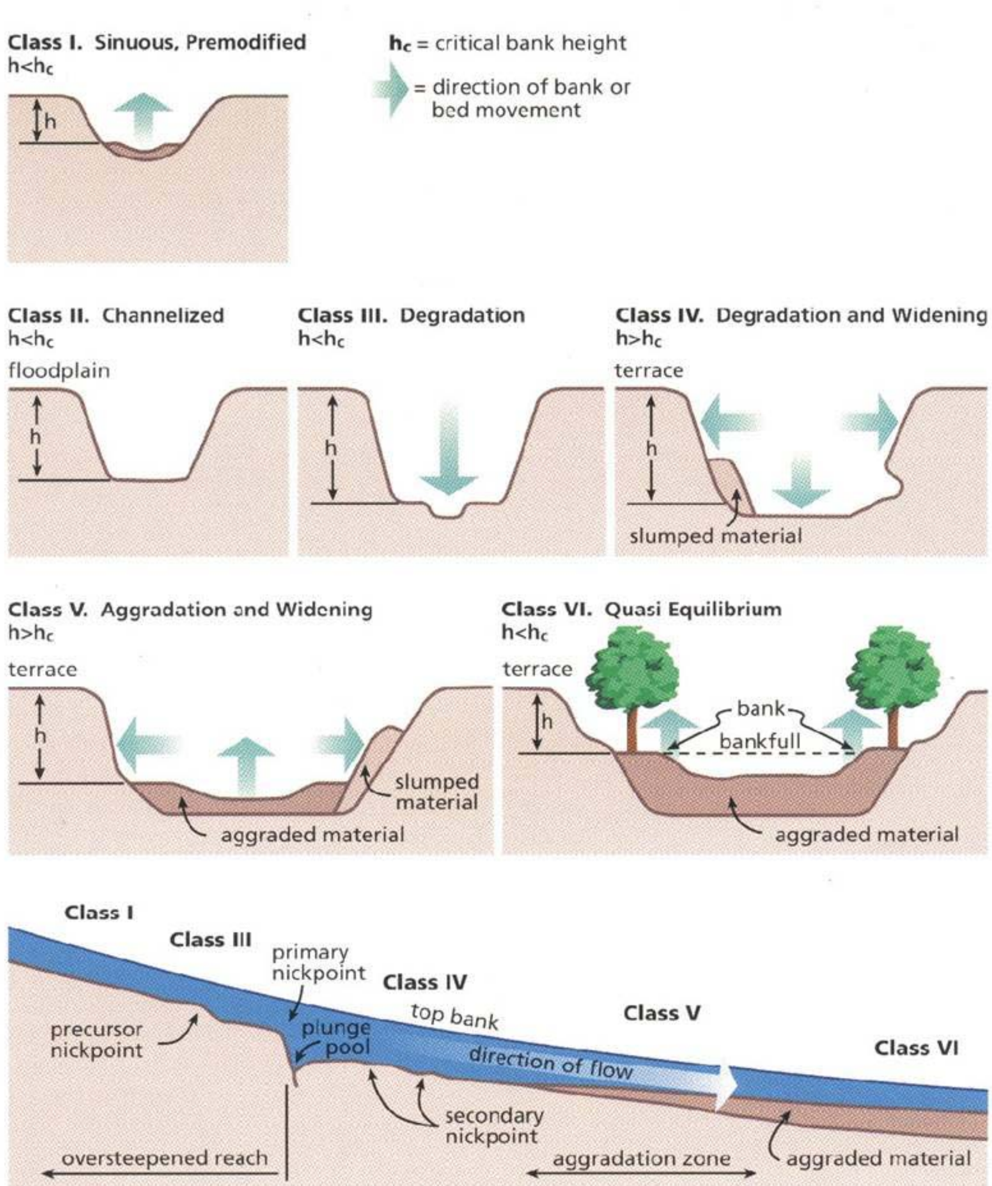

Figure 3. Channel Evolution Model (source: USDA 1998)

Generally speaking, the reaches represented in this report can be classified based on the Evolution Model. PS-2, PST1-2, PST2-3, PST5-4 and PS6/PS-7 can be classified as Class IV channels because they have experienced both degradation and widening. PS-4 is classified as Class V due to the aggradation and widening that is occurring in this reach. What seems likely though, in that some cases, the aggradation (class V) is due to alteration by creating a wider than normal cross-section (e.g. PS-5).

A second, but equally important concept is Lane's Balance, or the concept of channel equilibrium. This concept, also illustrated in **Figure 4**, assumes that channels work to produce equilibrium between erosive and resisting forces acting within the channel. This balance can be simplified to four parameters: sediment discharge, sediment particle size, stream flow and stream slope. Equilibrium occurs when all four are in balance; if one changes, there must be a proportional adjustment in the other parameters before new equilibrium is reached. These adjustments can occur over a range of time scales and in many cases systematic adjustments may be observed long after the initial perturbation has occurred. These observations are useful for making qualitative predictions and in explaining observed adjustments in channel geometry. As the larger downstream reaches 'feel' the accumulative adjustment of the upstream reaches downstream impacts can be dramatic. This is particularly true when the upstream reaches are adjusting in similar ways to similar pressures, such as oversupply of sediment due to logging and land clearing practices.

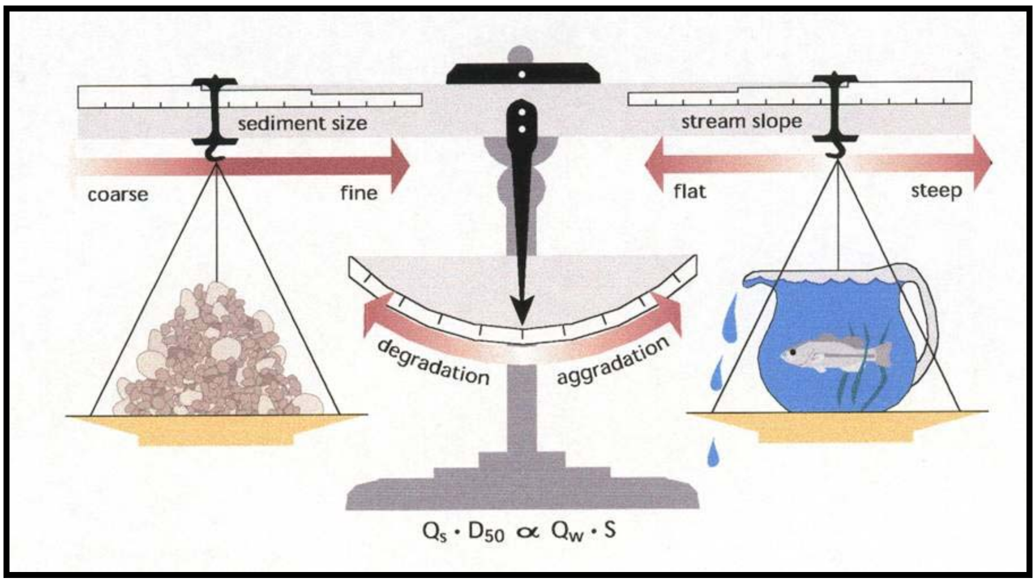

Figure 4. Lane's concept of stability (source: USDA, 1998)

Along the lower reaches of the Penjajawoc Stream Watershed, channel widening and aggradation were prevalent. The channel widening is likely a product of the channel attempting to retain its cross-sectional area even with systematic infilling. This may also be related to recent (over the last 10 years) high flow events.

Three general trends were observed within the Penjajawoc Stream and its tributaries. First, a linkage was observed between degradation and widening, indicating that reaches have a capacity and competency to erode and transport bed and bank sediments. Secondly, there were reaches where widening and aggradation dominated, indicating that reaches could erode their banks but without competency to transport sediment through the system. This may also indicate an oversupply of sediment and an attempt by the channel to maintain cross-sectional area. Finally, reaches displayed evidence of degradation and aggradation. This is likely an indication of dynamic bed load dominated channels which actively erode and transport sediment through 'pulses' (i.e. bars and other depositional features). These observations, in addition to anecdotal evidence of high flows and the historic assessment that illustrated sediment activation as a result of past land use practices, indicates that there is presently an over-supply of sediment within the system that can be readily reactivated. These points need to be addressed if restoration is to be effective within the watershed.

Aquatic Organism Passage at Road Crossings

Penjajawoc Stream and its tributaries are crossed by a well-developed network of roads. Although a few of the crossings are bridges spanning natural stream substrates, most crossings appear to be either concrete box culverts or large round, oval or arch culverts. Culverts that were installed above the streambed or have developed scour pools on their downstream ends are referred to as "perched" or "hanging" culverts. Currently, the Maine Department of Transportation and many natural resource agencies are promoting the restoration of passage for aquatic organisms as a Best Management Practice (BMP) for existing culverts, with strict guidelines for the design of new culverts to assure adequate passage.

Although aquatic organism passage was outside the purview of the fluvial geomorphic study commissioned by the DEP, passage BMPs should be considered as part of any comprehensive restoration plan for the Penjajawoc Stream watershed. Observations of several crossings were made during the field work for the fluvial geomorphic assessment, and provide a good representation of the opportunities that exist for the restoration of aquatic organism passage in the watershed.

"Aquatic organism" passage includes but is not limited to fish passage. Although fish have traditionally been the focus of passage concerns at culverts, aquatic organisms also include macroinvertebrates (e.g., aquatic insects, freshwater mussels, snails) and vertebrates (e.g., reptiles and amphibians). The most obvious barriers to passage are physical, where the height of the downstream culvert invert above the streambed exceeds the jumping or climbing ability of a given species. Culverts can also provide barriers by concentrating flows so that the accelerated velocities exceed the swimming ability of organisms. Wide, shallow flow through a culvert can also pose a barrier to species that favor deeper passage flow, with increased mortality from predators due to the lack of cover and escape routes.

Aquatic organism passage is important for several reasons. Species often move throughout watersheds to find refuge from predators, diminished water quality or high temperatures. The passage may also be important to access to breeding or rearing habitat, or a food supply. Inadequate passage can limit or even extirpate species' populations in some reaches, and it is not uncommon to have different fish assemblages upstream and downstream of these barriers.

Four crossings were selected as being representative of aquatic organism passage issues in the Penjajawoc Stream watershed. As discussed, a comprehensive survey of road crossings in the watershed was not performed, but is recommended to fully assess the extent of inadequate passage. Despite some obvious passage problems, many crossings in the watershed appear to provide adequate passage. Ultimately, basinwide passage restoration could perhaps be achieved by restoring passage at a small number of sites.

Reach PS-1: Upstream of Penjajawoc Stream–Penobscot River Confluence

During the field surveys, the shell of a rare species of freshwater mussel, the yellow lampmussel (*Lampsilis cariosa*) was found at the confluence of Penjajawoc Stream with the Penobscot River (**Photo 1**). The yellow lampmussel is a threatened species under the Maine Endangered Species Act. Although yellow lampmussels are usually found in medium to large rivers, their host fish species are white perch (*Morone americana*) and yellow perch (*Perca flavescens*), two species without strong swimming or leaping abilities who could easily be blocked by barriers at crossings. (All freshwater mussels rely on host aquatic species, typically fish, for the development of mussel larvae into subadults; larvae live on the host's gills for weeks or months before dropping off as tiny mussels.) Although it is unknown if yellow lampmussels would utilize habitat in Penjajawoc Stream, the species is illustrative of how passage problems for some species (i.e., white perch, yellow perch) could have wider ecological implications. Irregardless of the presence or absence of yellow lampmussels in Penjajawoc Stream, their presence at the confluence with the Penobscot River is important because known threats to the mussel (poor water quality and sedimentation) are issues for the stream.

The first potential barrier upstream of the Penobscot River is at the railroad trestle (**Photo 2**), where there is a steep drop comprised of large boulders. At least part of the trestle abutments may be founded on an outcropping of bedrock, perhaps indicating that a natural falls may have existed historically at the site. Despite its geology, upstream passage for aquatic organisms is not only challenged by the steepness of the drop but the width of the trestle opening. The width of the opening is much less than bankfull for the stream, and there is considerable streamflow passing underneath the abutments rather than in the channel (**Photo 3**). Penjajawoc Stream is of interest to the Maine Atlantic Salmon Commission (MASC) because it may serve as temperature refugia for adult Atlantic salmon (*Salmo salar*) in the Penobscot River (Joan Trial, MASC, personal communication). The abruptness of the drop, and lack of a well defined channel, may even pose a passage problem for a very strong swimmer and leaper such as an Atlantic salmon. Another anadromous (i.e., sea run) fish species that could potentially access habitat in Penjajawoc Stream is the blueback herring (*Alosa aestivalis*), which swims upstream from the Atlantic to spawn in freshwater riffles in the spring. The railroad crossing would definitely be a barrier to blueback herring, which are considered strong swimmers but have little leaping ability.

The Route 2 crossing, just upstream of the railroad trestle, is another barrier near the mouth of Penjajawoc Stream (**Photo 4**). The width of the opening is much less than bankfull, with the stream flowing over a concrete sill with a vertical drop. While the presence of bedrock may indicate historic falls at the site, it appears that the concrete sill has increased the height of the drop. Both the railroad trestle and Route 2 openings have poor alignments with the stream. At the Route 2 crossing, the abrupt change in alignment, width and slope may be contributing to long-term maintenance issues with the bridge, as evidenced by the sagging gabions on the upstream side of Route 2 (**Photo 5**). The poor condition of the crossing may eventually provide an opportunity to replace the structure or retrofit it with better passage.

Passage at both the railroad trestle and Route 2 could be improved through an engineered design. More evaluation would be required, but constructed riffles downstream of the crossings may be a possibility. Constructed riffles, or rock ramps, mimic natural stream channels at slopes as steep as 1:20 (vertical:horizontal), requiring a long run. Fish ladders, such as Denil or pool-and-weir fishways, can be constructed as steep as 1:6 for narrow openings, but their effectiveness is limited to strong-swimming fish species such as Atlantic salmon and a narrow range of streamflows. Almost any fish passage improvement for the two crossings would likely reduce the hydraulic capacity of the openings somewhat, which is a concern if the existing hydraulic capacities are already inadequate during floods; passage improvement could raise water levels upstream of the structures during floods. Passage improvement that widens the openings to bankfull width and changes their alignments to a more natural orientation with the stream would complement any design that addresses the steep slopes at the crossings, but this would require major work at the structures.

Reach PS-2: Mount Hope Avenue

The Mount Hope Avenue crossing consists of an arch culvert with concrete sill (**Photo 6**). The crossing does not appear to be very old, but obviously is a barrier to aquatic organisms at low stream flow. Although the width of the opening probably approaches bankfull flow, a scour pool downstream of the crossing has created a vertical drop that may be impassable to many species, especially at low flow. The crossing may have been constructed with adequate passage, but the erosion of the stream bed downstream of the culvert has lowered the grade, which is typical for many crossings.

Two techniques for restoring passage through the culvert may be feasible, but would require further study. One restoration technique would be to construct a riffle downstream of the culvert, with the riffle crest at or slightly above the downstream invert of the culvert, thereby backwatering the culvert. A second technique would be to reconstruct the streambed downstream of the culvert, raising the bed and sloping it up to the downstream invert of the culvert. A "natural" streambed could even be constructed up through the culvert, based on the "stream simulation" design for culverts championed by the U.S. Forest Service and others. Since both techniques could lower the hydraulic capacity of the culverts during floods, the capacity would have to be evaluated carefully to assure that the crossing still meets design flow criteria. It is also important that constructed riffles or streambeds fit in with the natural morphology of the stream, including pool-riffle sequencing, riffle slope, bankfull width, depth and velocity, and substrate size.

Even if passage is not improved downstream of Mount Hope Avenue (i.e., at the Route 2 and railroad crossings), improved passage at this culvert could help resident aquatic species in Penjajawoc Stream.

Reach Break PS-6/PS-7: Stillwater Avenue

While the culvert at Stillwater Avenue does not appear to be an obvious barrier to aquatic organisms, passage at the site is probably marginal due to the shallowness of the flow (**Photo 7**). Especially at low flows, depth and velocity may limit passage for some aquatic species. One retrofit for these culverts is to install a natural streambed, randomly placed structures (e.g., rocks, anchored to the bed), or baffles on the bottom of the culvert. Another retrofit would be the construction of a downstream riffle to backwater the culvert, increasing depth and lowering velocity. However, as discussed earlier, any culvert retrofits may reduce the hydraulic capacity of culverts during floods and would need to be evaluated further. The preferable option would be to replace this structure with a bridge or bottomless culvert with a natural streambed.

The biggest issue for the Stillwater Avenue crossing is whether further development in the area will create a passage barrier. Although there is not an obvious scour pool downstream of the culvert, urbanization in the watershed upstream of Stillwater Avenue could increase peak flows at the crossing, creating a scour pool and bed degradation. The crossing is most illustrative, however, of the issue of culvert *length*. Many aquatic species, such as fish, can sustain "burst" or "darting" speeds for short periods of time. Although these species might be able to negotiate the culvert at its current length, the crossing may become impassable if the culvert is lengthened. This may be a concern, given that strategic planning for the mall area suggests that Stillwater Avenue may eventually be widened, which would either require a longer culvert or two long culverts in series. Throughout the watershed, it is recommended that new stream crossings, or stream crossings that are lengthened, are designed to protect passage for aquatic organisms.

Photo 1. Mouth of Penjajawoc Stream looking downstream towards Penobscot River (July 19, 2005).

Photo 2. Penjajawoc Stream at railroad trestle near mouth (July 19, 2005).

Photo 3. Penjajawoc Stream at railroad trestle showing streamflow under abutment (July 19, 2005).

Photo 4. Penjajawoc Stream looking upstream through Route 2 crossing (July 19, 2005).

Photo 5. Penjajawoc Stream looking downstream towards Route 2 crossing; note slumped gabions on left (July 19, 2005).

Photo 6. Penjajawoc Stream looking upstream towards Mount Hope Avenue crossing (July 19, 2005).

Photo 7. Penjajawoc Stream looking upstream through Stillwater Avenue culvert (August 23, 2005).

5.0 EVALUATION OF STORMWATER MANAGEMENT

Based on the work undertaken and the results that have been discussed, it is apparent that some restoration work is warranted within the watershed. Two approaches to restoration, based on the scale of works, can be taken. The first, ad hoc or patchwork restoration which would generally consist of small scale, simple and inexpensive restoration projects, such as small scale bioengineering projects to stabilize sections of channel banks in order to decrease sediment supply and improve local habitat (i.e., greater riparian cover and reduced infilling of pools). As the impacts to the lowest reaches are an accumulation of upstream impacts, numerous small scale projects may lead to greater stability downstream. At the other end of the spectrum are large scale restoration projects involving wholesale change to channel configuration. These projects tend to involve large equipment, more detailed design and greater cost. The scale or strategy is dependent on the relative degree of channel disturbance, risk to property or infrastructure and potential to improve stream health and/or stability.

Based on the results of this work, any restoration work should be directed at controlling sediment input in the upper part of the watershed and main tributaries and controlling runoff from the headwaters through better conveyance systems or storage BMP's (Best Management Practices). Within the main Penjajawoc Stream, there are issues of channel migration, excessive bank erosion and sediment accumulation. While the large-scale removal of sediment may be beneficial in some reaches, it is a large and expensive proposition, and without control of upstream sediment sources, the success of the sediment removal is questionable. Focused stabilization work may be a better long-term solution, which may provide some enhancement to aquatic habitat.

Restoration Approach

Given the complex nature of the watershed and the active processes occurring within it, developing a true priority list for restoration is difficult. That being said, to provide an overall improvement in the watershed, reaches were prioritized for restoration based on their relative degree of channel disturbance, risk to property or infrastructure, and potential to improve stream health and/or stability. In prioritizing sites, an attempt was made to establish a balance between improving basic channel function and habitat concerns while accommodating local hazard issues. From reviewing the existing conditions within the watershed, two specific potential restoration themes were identified. The first is associated with several of the downstream reaches. These reaches, particularly PS-2 to PS-4, appear to be in a transitional/stressed state (i.e. widening, downcutting) due to changes in land use patterns which have influenced their hydrologic regime. In these catchments, development of water retention and detention features would allow expansion and creation of local wetland features and provide reduced peak flows. Furthermore, channel enhancement through the installation of riffle-pool sequences or grade control structures would reduce entrenchment and create more dynamically-stable channel systems; this would reduce flow velocities therefore decreasing the erosion capability during high flow events.

The second theme develops from a recurring observation along many of the upstream reaches of Penjajawoc Stream (PS-5 to PS7), which was the absence of deep pools, due, in part, to aggradation and bank erosion. Habitat improvements to the channel and greater floodplain could be provided by projects that provide minor reworking of channel geometry, including lowering of banks for better connectivity between channel and floodplain, deepening of pools to provide better low flow refuge and greater channel variability (diversity of habitat), and sculpting of bar material to reduce channel curvature and bank erosion rates. This would increase local shear by increasing gradients and water depth in the channel, thus improving sediment conveyance. Better connectivity between floodplain and river will enhance those habitat features in the floodplain. These improvements could be strategically done in areas where the river migration is also a hazard to permanent structures (i.e. roads) and property.

Riparian Condition

The riparian corridor along Penjajawoc Stream influences water quality. Herbaceous and woody vegetation (trees and shrubs) on the stream margins provides shade and cover for wildlife, protects against bank erosion, buffers that stream from non-point source pollution, and contributes woody debris and leaf litter to the stream. In low gradient streams with small substrates, large and small woody debris are important instream habitat features, and many macroinvertebrates rely on leaf litter for food and cover. In general, Penjajawoc stream is poorly buffered. Although the dearth of woody vegetation in some stream reaches is related to urbanization, the area's historic use as farmland probably contributed to a lot of clearing of the riparian zone, a condition that persisted for decades if not more than a century. Many of the wooded riparian areas appear to be monocultures of short-lived species (e.g. the quaking aspen, *Populus tremuloides*) that colonize old fields and pastures. Restoration activities that restore diverse, native tree and shrub buffers to the banks, floodplains and uplands adjacent to Penjajawoc Stream should be encouraged.

Priority Sites

A range of work could be undertaken, from the small-scale (i.e. control erosion), to moderate size, that involves more materials, time and planning. Listed below are the reaches where restoration work is recommended; **Appendix D** also summarizes the various methods of restoration. The list is in reach order as there is no priority sequence. For each reach, a summary of problems and generic approaches are provided. These sites represent a range of possible work to address the various problems within the watershed, and thus provide examples of the type and nature of restoration that could be undertaken in the future.

PS-2

Existing Conditions

Reach PS-2 flows from Mount Hope Avenue to Route 2. RSAT results indicated a moderate degree of stream health and a transitional or stressed state. Dominant geomorphic processes affecting the reach were degradation and widening. Evidence of theses processes included exposed bridge footings, undermined gabion baskets, basal scour along both of riffle and fallen or leaning trees. Bankfull widths and depths ranged from 8-12 meters (26-39 ft) and 0.5-1.5 meters (1.5-5 ft), respectively. Upstream of Route 2, residential properties had begun to encroach on the channel through bank protection measures and channel hardening. Many of these structures are currently experiencing some form of failure.

Potential Restoration

- Introduce grade control features in order to reduce local erosion and trap sediment
- Local bank stabilization to reduce sediment inputs (may include re-grading and plantings / live staking or other bioengineering techniques).

Functions Enhanced

- Restore balanced sediment transport through area
- Aquatic and wildlife habitat.

PS-3

Existing Conditions

Reach PS-3 (East of Hogan Road and North of Mount Hope Avenue) was impacted by beaver activity, with several large dams causing extensive backwater areas and associated sediment deposition. Beaver activity is a natural stream occurrence, with evidence of past and recent beaver activity throughout the watershed. Beaver management can be difficult. Beavers and their dams are native to the area. Restoration activities should recognize the beaver activity and try to incorporate more preferable habitat in side/floodplain areas to limit their influence along the main channel. Bankfull widths ranged from 5-10 meters (16-33 ft), while bankfull depths ranged from 0.5-1.2 meters (1.5-4 ft). Bed materials were dominated by sand with some cobble and gravel. Rapid assessment scores indicated an overall moderate degree of stream health and a transitional or 'stressed' geomorphic state. Aggradation dominated with coarse materials in riffles embedded and medial bar formation

Potential Restoration

- Bank stabilization, including bioengineering techniques.

Functions Enhanced

- Reduce sediment pulses from upstream areas.
- Reduce sediment input from bank erosion.
- Improved habitat

PS-4

Existing Conditions

Reach PS-4 bankfull channel dimensions ranged 6-7 meters (19-23 ft) in width and 0.6-0.9 meters (2-3 ft) in depth. Substrate throughout the majority of the reach consisted of gravel to cobble substrate. Disturbances to the channel included an old decommissioned crossing and failed culvert. Overall, the reach exhibited a moderate degree of health and transitional/stressed state. Aggradation and widening were the dominant geomorphic processes affecting the reach, with lobate bars, accretion on point bars and exposed tree roots providing evidence.

Potential Restoration

- Widen channel to accommodate larger flow events and reduce local erosion.
- Local bank stabilization to reduce sediment inputs (may include re-grading and plantings / live staking or other bioengineering techniques).

Functions Enhanced

- Reduce sediment pulses from upstream areas.
- Reduce sediment input from bank erosion.
- Improved habitat

PS-5

Existing Conditions

Reach PS-5 had very steep banks with several by-pass channels and stormwater ponds present on both sides of the floodplain. A substantial amount of wetland vegetation was present in the active channel, while some small gravel deposits were observed along the channel margins. A large scour pool had developed downstream of the culvert at the upstream portion of the reach. PS-5 scored a moderate degree of stream health but was determined to be in an active state of adjustment through the RGA score. Widening was the predominant geomorphic process affecting the reach, with exposed tree roots, fracture lines along top of bank and basal scour over >50% of the reach being noted at the site.

Potential Restoration

- Bank stabilization, including bioengineering techniques.
- Re-grade and stabilize banks to control channel migration.

Functions Enhanced

- Stabilize channel to reduce sediment inputs from banks.
- Control sediment supply / transport.

PS-6

Existing Conditions

Reach PS-6 scored as transitional (stressed) with widening being the dominant geomorphic process affecting the reach. Exposed bedrock provided a grade control along a section of the reach and several manholes were observed within the floodplain. Riparian vegetation consisted of dense alder shrubs along with herbaceous and grassy species. Substrate was relatively coarse, with cobbles to gravel composing the riffles and gravel to sand found in the pools. Bankfull widths ranged from 6-8 meters (20-26 ft) and depths from 0.6-1.0 meters (2-3.3 ft). The reach displayed a moderate degree of stream health.

Potential Restoration

- Structure stability / re-grade embankment.
- Add channel structure (step-pool sequence).

Functions Enhanced

- Channel stability.
- Aquatic habitat / fish passage.

PS-7

Existing Conditions

Reach PS-7's morphology was dominated by presence of several old beaver dams that had been breeched and their associated deposits of fine substrate. Bankfull widths measured 5-8 meters (16-26 ft) while bankfull depths measured 0.4-0.9 meters (1.3-3 ft). Riparian vegetation consisted of grassy and herbaceous species with shrubs along the sinuous channel. Bank stabilization measures had been undertaken recently behind a professional building. Overall, the reach displayed a moderate degree of stream health and was geomorphologically stable, with some aggradation occurring.

Potential Restoration

- Re-grade banks.
- Bank stabilization, including bioengineering techniques.
- Narrow the channel to enhance sediment transport.

Functions Enhanced

- Sediment supply reduced (bank erosion).
- Sediment transport.
- Aquatic and wildlife habitat.

6.0 SUMMARY AND CONCLUSIONS

A comprehensive assessment of the physical processes occurring within the Penjajawoc watershed has been completed within the monitoring timeframe of August to November 2005. Based on the assessment, field work, monitoring and analyses, substantial information on channel processes and the overall watershed behaviour has been obtained and site specific restoration recommendations were developed.

In general, results of monitoring data indicate that Penjajawoc Stream and tributaries has experienced minimal change in erosion rates and cross-sectional shape and area. In addition, there is a slight variation between the bed material being mobilized for the silt dominated section and this can be applied to the cross sections dominated by cobbles. In terms of the stream data analysis, there were three general trends that were observed within the Penjajawoc Stream and its tributaries. These three trends indicate that there is presently an over-supply of sediment within the systems that can be readily reactivated due to evidence of high flows and the result of past land use practices. These issues need to be addressed if restoration is to be effective within the watershed.

It is recommended that monitoring be continued to better clarify trends of erosion and deposition. The values collected do not provide an accurate estimate of long term channel trends due to the limited period of monitoring to date. Furthermore, with the continuation of monitoring (i.e. minimum once a year and after each major large flow), changes in channel form and trends of erosion and deposition will become more transparent. This way the appropriate restoration approaches will be taken. If these issues are not addressed, bank erosion, for example, on Penjajawoc Stream will continue to threaten water quality, aquatic habitat, and public and private infrastructure unless a sustainable morphology can be re-established in several key reaches.

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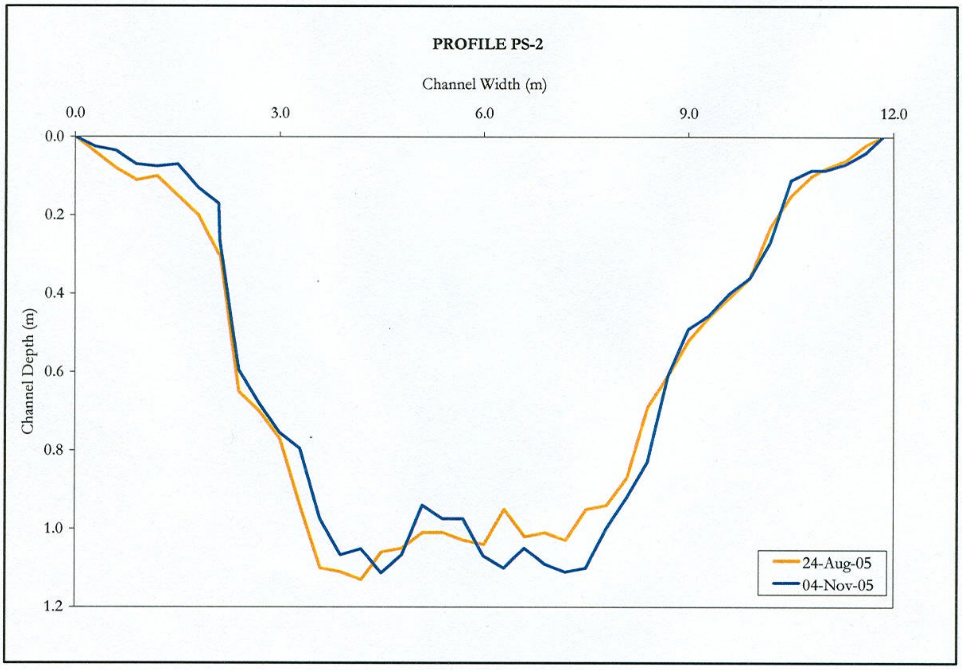
Appendix A

CHANGE IN CROSS SECTIONAL AREA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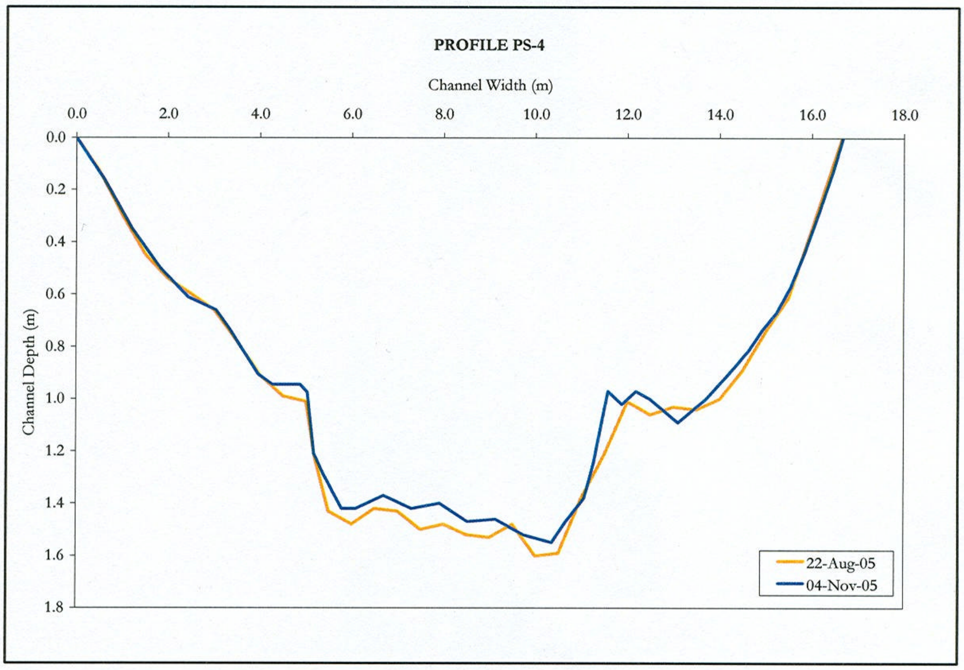
04-Nov-05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Channel Depth (m)
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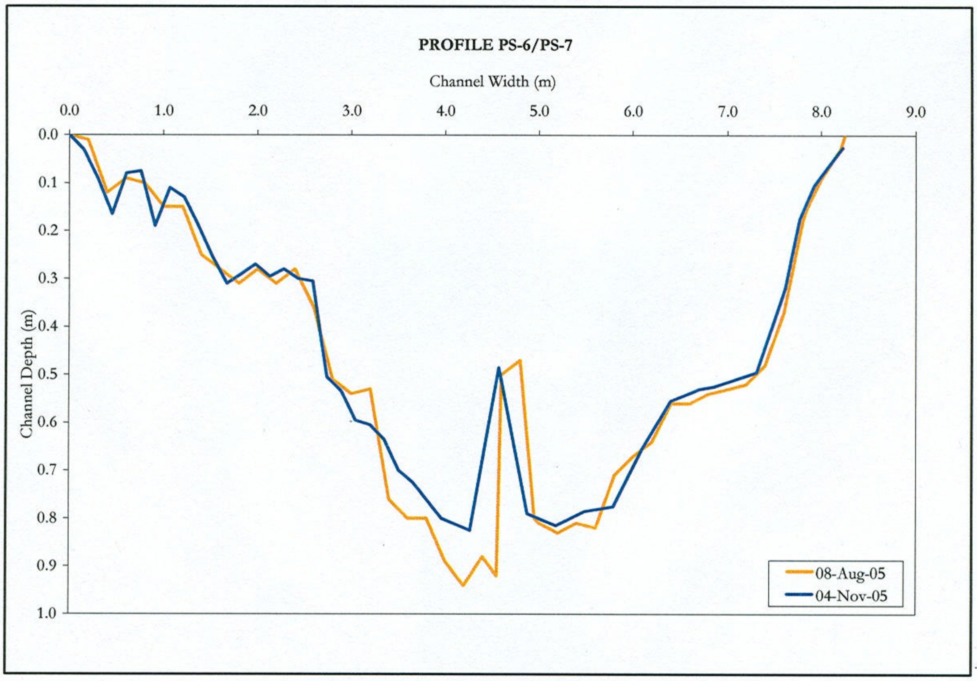
04-Nov-05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Channel Depth (m)
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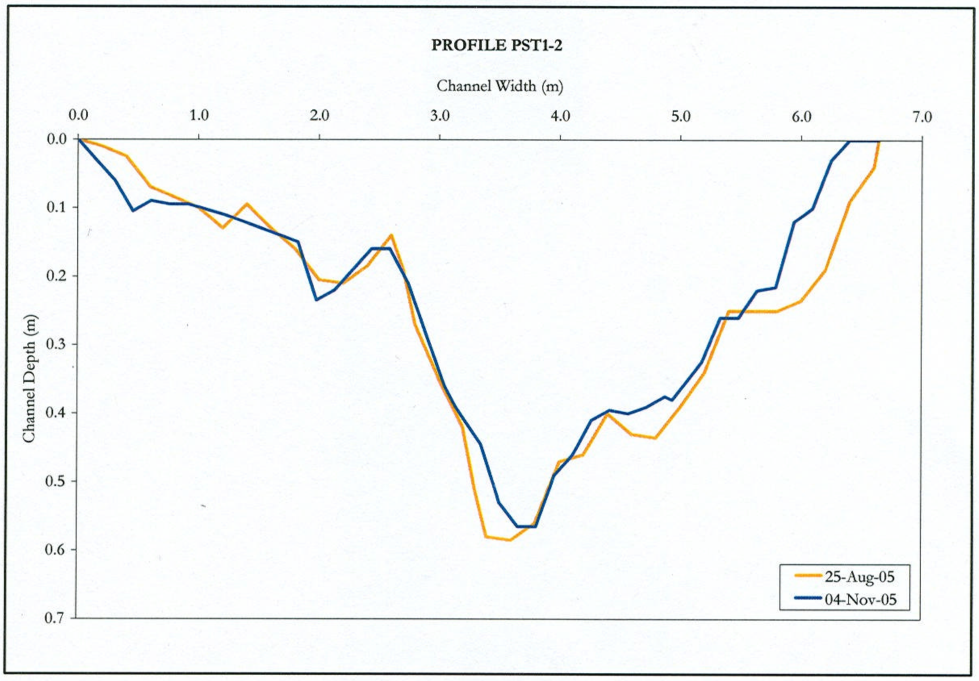
04-Nov-05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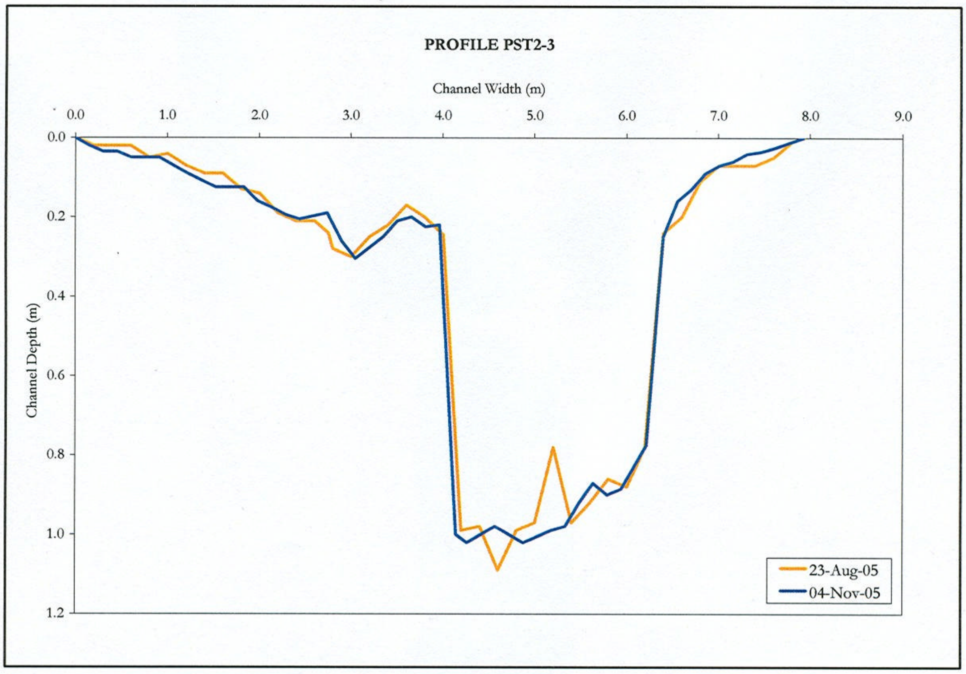
04-Nov-05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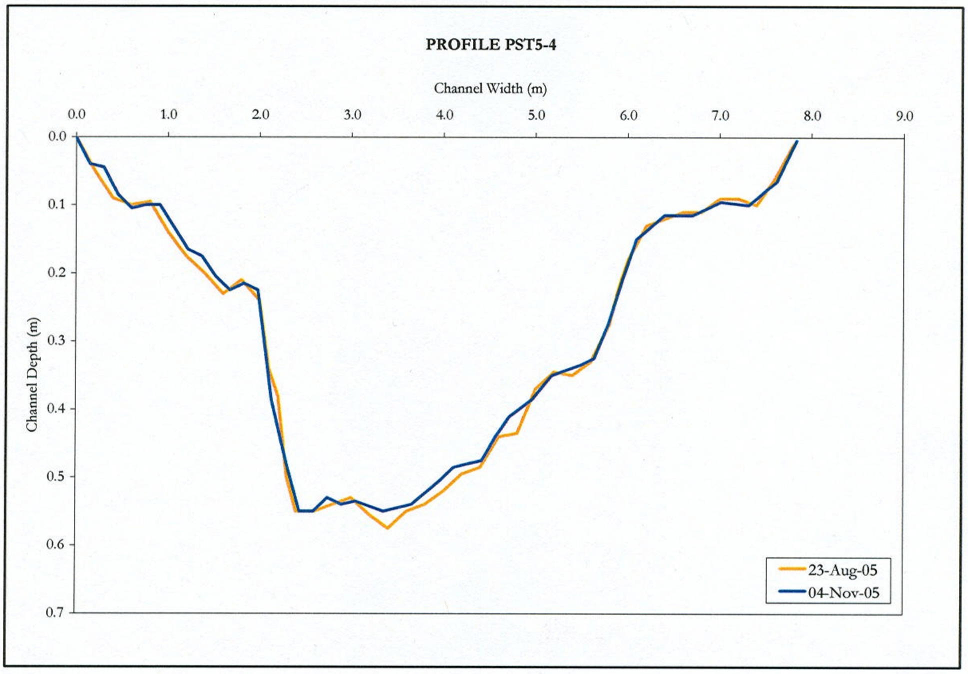
23-Aug-05
04-Nov-05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Channel Depth (m)
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0.2
0.3
0.4
0.5
0.6
0.7
23-Aug-05
04-Nov-05

Appendix B

SUMMARY OF DETAILED FIELD WORK

FLUVIAL GEOMORPHOLOGY SUMMARY

Penjajawoc Stream - Reach PS2

Site Location:	Reach PS2	
Length surveyed:	751.97	ft
Number of cross-sections:	10	
Date of Survey:	AUG.24/25, 2005	

Controlling Factors

Upstream Drainage Area:	
Geology / Soils:	N/A

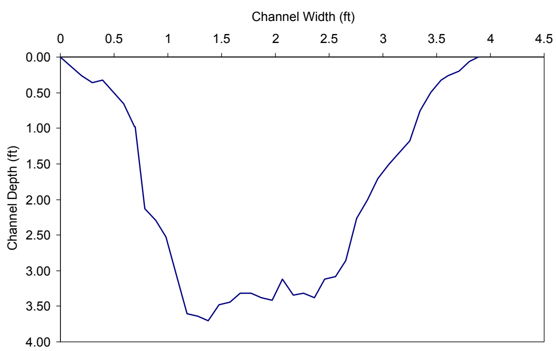
Modifying Factors

Surrounding Land Use:	wet meadow
General Riparian Vegetation:	tall herbs and grasses, rare shrubs
Existing Channel Disturbances:	none
Woody Debris:	occasional minor woody debris in channel, occasional major woody debris along banks

Cross-Sectional Characteristics

	Range	Average
Bankfull Width (ft)	13.55 - 38.85	19.73
Bankfull Depth (ft)	1.44 - 1.99	1.71
Width / Depth	8.23 - 20.43	11.58
Wetted Width (ft)	5.09 - 17.36	10.93
Water Depth (ft)	0.33 - 1.04	0.50
Width / Depth	9.08 - 44.95	24.76
Entrenchment (ft)	68.80 - 164.34	103.06
Entrenchment Ratio	3.51 - 9.84	5.49

Bankfull Cross Section #4



Bank Characteristics

	Range	Average
Bank Height (ft)	0 - 9.84	3.7
Bank Angle (degrees)	6 - 36	18.1
Root Depth (in)	2.0 - 9.06	5.7
Root Density ***(1=Low - 5=High)***	1 - 2	1.4
Protected by vegetation (%)	5 - 70	29.0
Amount of undercut (in)	0.0 - 7.48	0.87
Banks with undercuts (%)		21%

Bank Materials	**Torvane values (kg/cm2)**
si/vfs/roots	0.19
ms/fs/si	0.11
vfs/ms/si	0.17
si/ms	0.20
si/fs	0.19
wet silt	0.18
vfs	0.21
cl/si	0.24

* - Dominant Material

FLUVIAL GEOMORPHOLOGY SUMMARY

Penjajawoc Stream - Reach PS2

Planform Characteristics

Long Profile (avg)

Bankfull Gradient:	0.25	%
Inter-Pool Gradient:	0.59	%
Inter-Riffle Gradient:	0.51	%
Riffle Gradient:	3.21	%
Riffle Length:	16.77	ft
Riffle-Pool Spacing:	44.09	ft
Max Pool Depth:	4.068	ft

Substrate Characteristics

		Range	Average
Particle Shape (in)			
	X	.79-18.5	4.4
	Y	.39-14.17	2.9
	Z	.39-8.66	1.7
Hydraulic Roughness (in)			
	Maximum	1.97-29.53	5.02
	Median	.39-1.97	0.37
	Minimum	.0001-.23	0.04
Embeddedness (%)		10 - 40	21.5

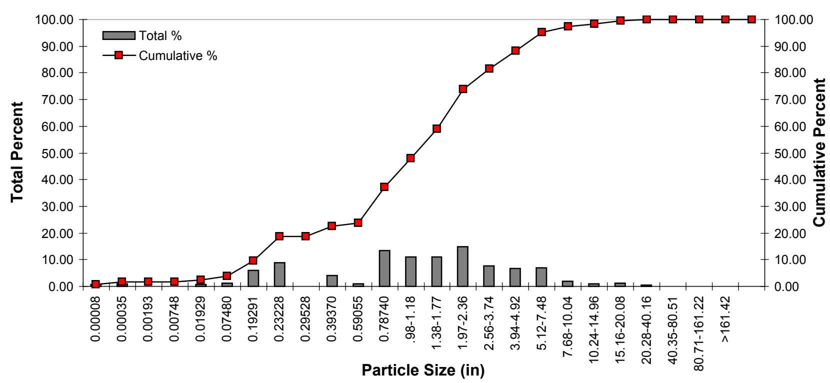
Sub-pavement

- described as being clay

Particle Sizes (in)

	Pebble Counts	
D10	0.14	in
D50	1.19	in
D90	4.87	in

Substrate Particle Size Distribution Based on Pebble Counts



FLUVIAL GEOMORPHOLOGY SUMMARY

Penjajawoc Stream - Reach PS4

Site Location:	Reach PS4
Length surveyed:	1233.92 ft
Number of cross-sections:	10
Date of Survey:	AUG.22, 2005

Modifying Factors

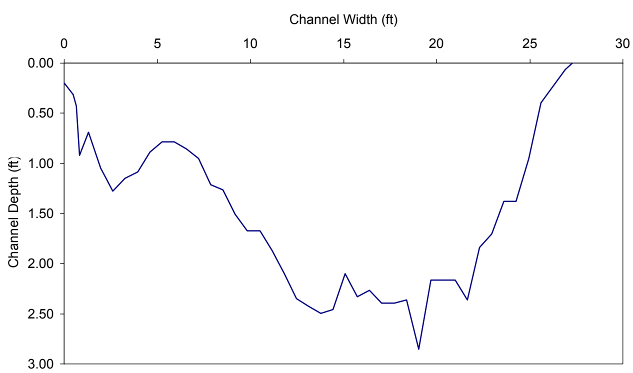
Surrounding Land Use:	meadow/scrubland
General Riparian Vegetation:	tall herbs and grasses,
Existing Channel Disturbances:	none

Woody Debris: occasional minor woody debris in channel, occasional major woody debris along banks

Cross-Sectional Characteristics

		Average
Bankfull Width (ft)	14.27 - 57.91	23.65
Bankfull Depth (ft)	1.18 - 3.32	1.92
Width / Depth	6.60 - 19.39	12.85
Wetted Width (ft)	8.66 - 18.73	11.88
Water Depth (ft)	0.21 - 1.09	0.52
Width / Depth	9.66 - 61.96	32.26
Entrenchment (ft)	19.46 - 244.78	85.33
Entrenchment Ratio	1.13 - 16.18	4.64

Bankfull Cross Section #6



		Average
Bank Height (in)	2.62 - 8.2	4.38
Bank Angle (degrees)	6 - 55	21
Root Depth (in)	1.6 - 35.43	10.2
Root Density ***(1=Low - 5=High)***	1 - 4	2.1
Protected by vegetation (%)	10 -	

Penjajawoc Stream - Reach PS4

Planform Characteristics

Long Profile (avg)

Bankfull Gradient:	0.95	%
Inter-Pool Gradient:	0.42	%
Inter-Riffle Gradient:	0.75	%
Riffle Gradient:	2.62	%
Riffle Length:	21.03	ft
Riffle-Pool Spacing:	37.47	ft
Max Pool Depth:	3.71	ft

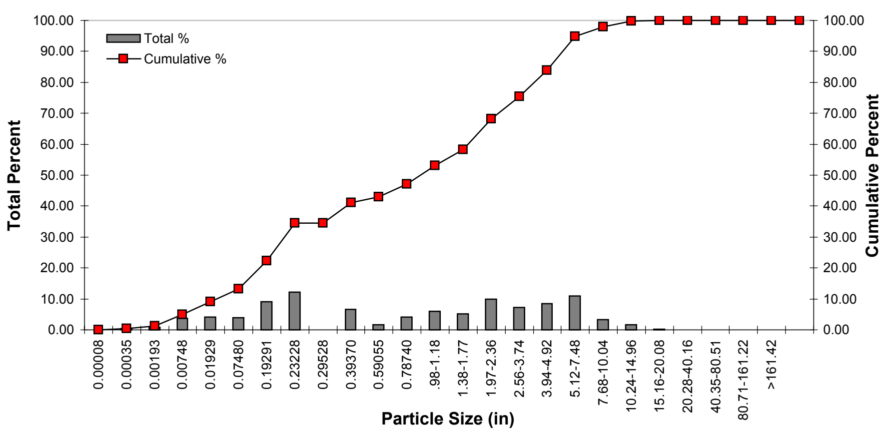
Substrate Characteristics

		Range	Average
Particle Shape (in)			
	X	2.76-10.24	6.0
	Y	1.97-7.09	3.6
	Z	.79-3.54	6.0
Hydraulic Roughness (in)			
	Maximum	3.94-16.93	8.66
	Median	.39-2.36	1.24
	Minimum	.0001-.19	0.03
Embeddedness (%)		10 - 90	37.5

Particle Sizes (in)

	Pebble Counts	
D10	0.021	in
D50	0.94	in
D90	5.47	in

Substrate Particle Size Distribution Based on Pebble Counts



FLUVIAL GEOMORPHOLOGY SUMMARY

Penjajawoc Stream - Reach PS6/PS7

Site Location:	Reach PS6/PS7
Length surveyed:	829.40 ft
Number of cross-sections:	8
Date of Survey:	AUG.25, 2005

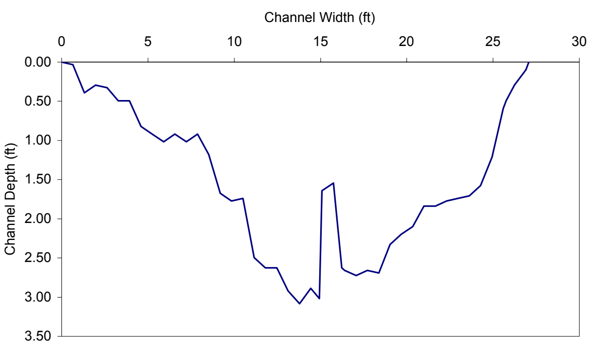
Modifying Factors

Surrounding Land Use:	scrubland, commercial area,
General Riparian Vegetation:	tall herbs and grasses, rare shrubs
Existing Channel Disturbances:	none
Woody Debris:	occasional minor woody debris in channel, occasional major woody debris along banks

Cross-Sectional Characteristics

		Average
Bankfull Width (m)	17.65 - 29.43	77.76
Bankfull Depth (m)	1.22 - 1.85	4.97
Width / Depth	10.36 - 24.04	15.98
Wetted Width (m)	8.43 - 16.01	11.14
Water Depth (m)	0.18 - 1.31	0.48
Width / Depth	11.18 - 67.68	34.25
Entrenchment (m)	26.41 - 168.14	84.60
Entrenchment Ratio	1.23 - 7.23	3.65

Bankfull Cross Section #6



Bank Characteristics

		Average
Bank Height (m)	2.30 - 5.91	3.59
Bank Angle (degrees)	11 - 55	27.4375
Root Depth (in)	3.9 - 23.62	9.4
Root Density ***(1=Low - 5=High)***	1 - 10	3.6
Protected by vegetation (%)	10 - 95	61.3
Amount of undercut (in)	0.0 - 4.72	0.49
Banks with undercuts (%)		21%

Bank Materials	**Torvane values (kg/cm2)**
si/cl	0.27
si/cl/fs	0.22
cl/si/gravel	0.27
si/fs/vfs	0.27
si/cl/roots	0.27

* - Dominant Material

FLUVIAL GEOMORPHOLOGY SUMMARY

Penjajawoc Stream - Reach PS6/PS7

Planform Characteristics

Long Profile (avg)

Bankfull Gradient:	0.58	%
Inter-Pool Gradient:	0.79	%
Inter-Riffle Gradient:	0.86	%
Riffle Gradient:	3.29	%
Riffle Length:	20.57	ft
Riffle-Pool Spacing:	38.16	ft
Max Pool Depth:	3.31	ft

Substrate Characteristics

Particle Shape (in)		**Range**	**Average**
	X	1.57-22.44	5.66
	Y	1.18-17.72	4.25
	Z	.39-9.45	1.98
Hydraulic Roughness (in)			
	Maximum	1.57-20.47	6.25
	Median	.20-1.97	1.01
	Minimum	.0004-.20	0.09
Embeddedness (%)		60 - 95	83.1

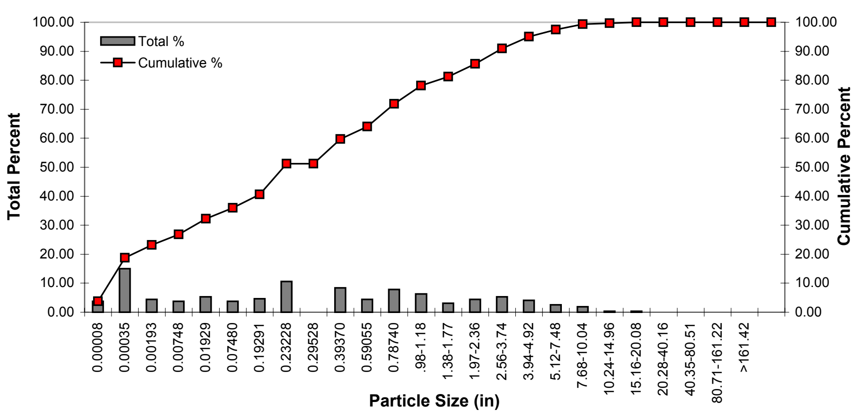
Sub-pavement

cl	16.25	**P**	15.00
si	3.13	**.39in**	10.63
vfs	1.25	**.59in**	5.63
fs	5.00	**.79in**	8.75
ms	6.88	**1.18in**	2.50
cs	9.38	**1.57in**	3.75
vcs	11.88	**1.97in**	0.00
		Bdr.	0.00

Particle Sizes (in)

	Pebble Counts	
D10	0.0001	in
D50	0.2574	in
D90	2.9809	in

Substrate Particle Size Distribution Based on Pebble Counts



FLUVIAL GEOMORPHOLOGY SUMMARY

Penjajawoc Stream - Reach PST1/2

Site Location:	Reach PST1/2
Length surveyed:	795.60 ft
Number of cross-sections:	8
Date of Survey:	AUG.25, 2005

Controlling Factors

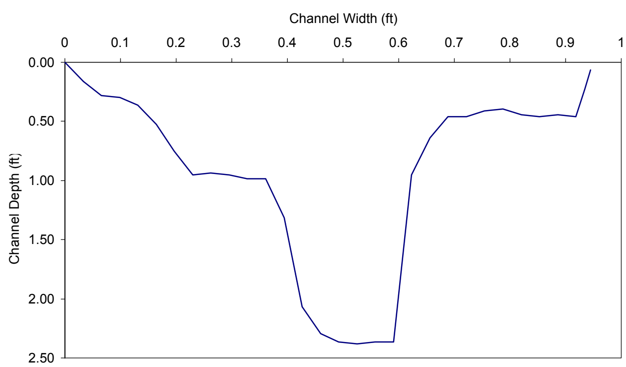
Modifying Factors

Surrounding Land Use:	wet meadow
General Riparian Vegetation:	tall herbs and grasses, rare shrubs
Existing Channel Disturbances:	none
Woody Debris:	occasional minor woody debris in channel, occasional major woody debris along banks

Cross-Sectional Characteristics

		Average
Bankfull Width (ft)	9.45 - 21.78	13.97
Bankfull Depth (ft)	0.55 - 1.33	0.94
Width / Depth	9.01 - 35.52	16.39
Wetted Width (ft)	-0.89 - 5.74	2.76
Water Depth (ft)	0.20 - 1.55	0.75
Width / Depth	-1.96 - 11.17	4.72
Entrenchment (ft)	68.64 - 208.83	153.40
Entrenchment Ratio	3.53 - 21.69	12.44

Bankfull Cross Section #6



Bank Characteristics

		Average
Bank Height (m)	0.66 - 3.28	1.99
Bank Angle (degrees)	3 - 29	10.5
Root Depth (in)	2.4 - 11.81102	6.4
Root Density ***(1=Low - 5=High)***	1 - 3	2.0
Protected by vegetation (%)	90 - 100	91.3
Amount of undercut (in)	0.0 - 11.81	1.57
Banks with undercuts (%)		21%

Bank Materials	**Torvane values (kg/cm2)**
cl/si	0.19
si/roots	0.48
si/cl/vfs	0.24
si/fs	0.25
cl/si/roots	0.26

* - Dominant Material

Penjajawoc Stream - Reach PST1/2

Planform Characteristics

Long Profile (avg)

Bankfull Gradient:	0.10	%	
Inter-Pool Gradient:	NA	%	
Inter-Riffle Gradient:	NA	%	
Riffle Gradient:	NA	%	
Riffle Length:	NA	ft	
Riffle-Pool Spacing:	NA	ft	
Max Pool Depth:	3.15	ft	- measured at the backwater area

Substrate Characteristics

		Range	Average
Particle Shape (in)			
	X	1.97-7.87	4.1
	Y	1.18-6.30	3.0
	Z	.79-5.91	2.3
Hydraulic Roughness (in)			
	Maximum	0-5.91	1.7
	Median	0-.20	0.0
	Minimum	0-0.0004	0.0003
Embeddedness (%)		80 - 100	97.5

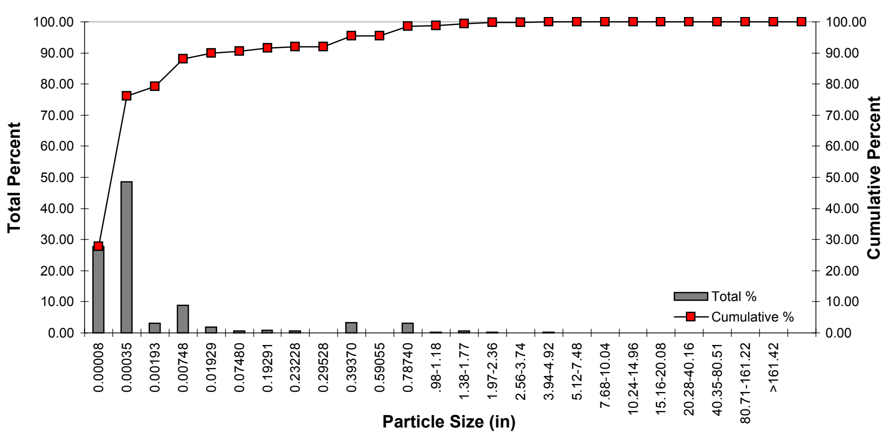
Sub-pavement

cl	37.5	**P**	2.5
si	45	**.39in**	2.5
vfs	5	**.59in**	1.25
fs	1.25	**.79in**	0
ms	1.25	**1.18in**	0
cs	1.25	**1.57in**	0
vcs	2.5	**1.97in**	0
		Bdr.	0

Particle Sizes (in)

	Pebble Counts	
D10	clay	in
D50	silt	in
D90	0.02	in

Substrate Particle Size Distribution Based on Pebble Counts



FLUVIAL GEOMORPHOLOGY SUMMARY

Penjajawoc Stream - Reach PS2/3

Site Location:	PENJAJAWOC STREAM
Length surveyed:	721.78 ft
Number of cross-sections:	10
Date of Survey:	AUG.24/25, 2005

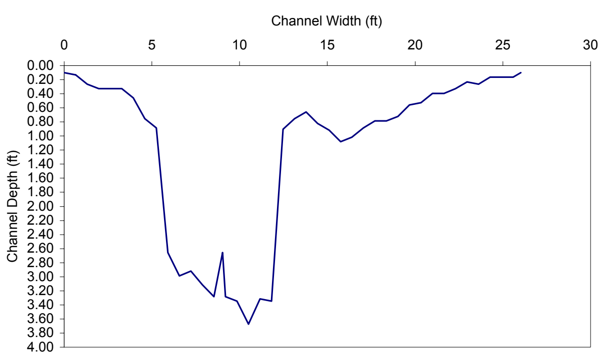
Modifying Factors

Surrounding Land Use:	Powerline corridor, scrub/forested area
General Riparian Vegetation:	tall herbs and grasses, trees
Existing Channel Disturbances:	Hydro pole inserted into bank (used as Benchmark)
Woody Debris:	occasional minor woody debris in channel, occasional major woody debris along banks

Cross-Sectional Characteristics

		Average
Bankfull Width (ft)	7.71 - 26.02	13.41
Bankfull Depth (ft)	0.62 - 2.14	1.27
Width / Depth	5.46 - 21.52	11.60
Wetted Width (ft)	2.40 - 9.58	5.38
Water Depth (ft)	0.06 - 0.57	0.24
Width / Depth	10.81 - 66.37	30.36
Entrenchment (ft)	60.47 - 175.56	131.52
Entrenchment Ratio	2.32 - 15.25	10.85

Bankfull Cross Section #7



Bank Characteristics

		Average
Bank Height (ft)	1.31 - 29.53	3.86
Bank Angle (degrees)	2.0 - 42	12.75
Root Depth (in)	1.57 - 19.685	8.33
Root Density ***(1=Low - 5=High)***	1 - 3	1.60
Protected by vegetation (%)	15 - 90	53.75
Amount of undercut (in)	0 - 7.87	1.57
Banks with undercuts (%)		21%

Bank Materials	**Torvane values (kg/cm2)**
si/fs	0.19
si/ms	0.05
cl/si	0.12
si/vfs	0.15
si/fs/roots	0.19

* - Dominant Material

Penjajawoc Stream - Reach PS2/3

Planform Characteristics

Long Profile (avg)

Bankfull Gradient:	1.00	%
Inter-Pool Gradient:	1.35	%
Inter-Riffle Gradient:	1.53	%
Riffle Gradient:	3.66	%
Riffle Length:	21.36	ft
Riffle-Pool Spacing:	66.27	ft
Max Pool Depth:	3.05	ft

Substrate Characteristics

		Range	Average
Particle Shape (in)			
	X	1.18-8.66	4.4
	Y	.79-6.3	2.9
	Z	.39-3.54	1.9
Hydraulic Roughness (in)			
	Maximum	1.18-28.35	9.4
	Median	.07-108.39	1.2
	Minimum	.2-.0004	0.1
Embeddedness (%)		10 - 90	46.0

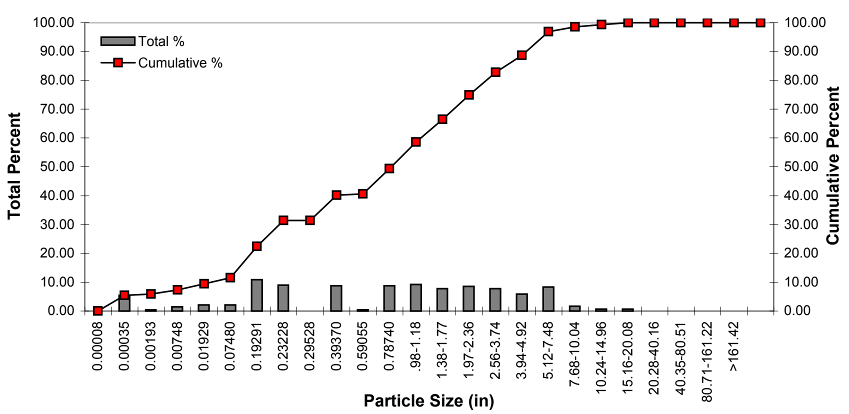
Sub-pavement

- described as being clay

Particle Sizes (in)

	Pebble Counts	
D10	0.02	in
D50	0.81	in
D90	4.72	in

Substrate Particle Size Distribution Based on Pebble Counts



Penjajawoc Stream - Reach PST5/4

Site Location:	Reacj PST5/4
Length surveyed:	716.21 ft
Number of cross-sections:	10
Date of Survey:	AUG.23, 2005

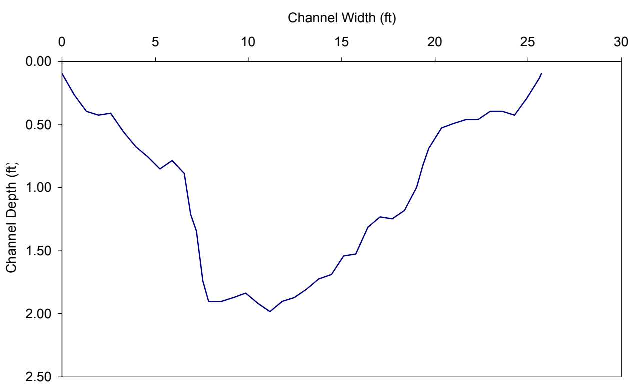
Modifying Factors

Surrounding Land Use:	wet meadow
General Riparian Vegetation:	tall herbs and grasses, rare shrubs
Existing Channel Disturbances:	none
Woody Debris:	occasional minor woody debris in channel, occasional major woody debris along banks

Cross-Sectional Characteristics

	Range	Average
Bankfull Width (ft)	7.68 - 25.72	12.29
Bankfull Depth (ft)	0.60 - 1.29	0.88
Width / Depth	8.64 - 25.29	14.35
Wetted Width (ft)	1.94 - 7.15	5.32
Water Depth (ft)	0.06 - 0.49	0.21
Width / Depth	10.69 - 85.64	35.64
Entrenchment (ft)	31.07 - 222.57	101.69
Entrenchment Ratio	2.73 - 18.09	9.06

Bankfull Cross Section #9



Bank Characteristics

	Range	Average
Bank Height (ft)	1.31 - 2.62	1.76
Bank Angle (degrees)	3 - 21	10.5
Root Depth (in)	0.8 - 11.81	4.6
Root Density ***(1=Low - 5=High)***	1 - 2	1.3
Protected by vegetation (%)	20 - 80	41.0
Amount of undercut (in)	0.0 - 9.84	1.95
Banks with undercuts (%)		21%

Bank Materials	**Torvane values (kg/cm2)**
si/vfs/roots	0.18
Org.mat/roots	0.18
Org.soil	0.23
Org.soi/ms	0.26
rts/si/sand	0.55
ms/fs/si	0.18
si/ms/roots	0.18

* - Dominant Material

Penjajawoc Stream - Reach PST5/4

Planform Characteristics

Long Profile (avg)

Bankfull Gradient:	1.85	%
Inter-Pool Gradient:	1.74	%
Inter-Riffle Gradient:	1.66	%
Riffle Gradient:	3.72	%
Riffle Length:	14.27	ft
Riffle-Pool Spacing:	45.34	ft
Max Pool Depth:	1.05	ft

Substrate Characteristics

		Range	Average
Particle Shape (in)			
	X	1.18-7.48	3.6
	Y	.79-5.12	2.4
	Z	.39-2.76	1.2
Hydraulic Roughness (in)			
	Maximum	1.18-11.81	6.8
	Median	.20-.79	0.5
	Minimum	.0004-.23	0.03
Embeddedness (%)		20 - 70	43.0

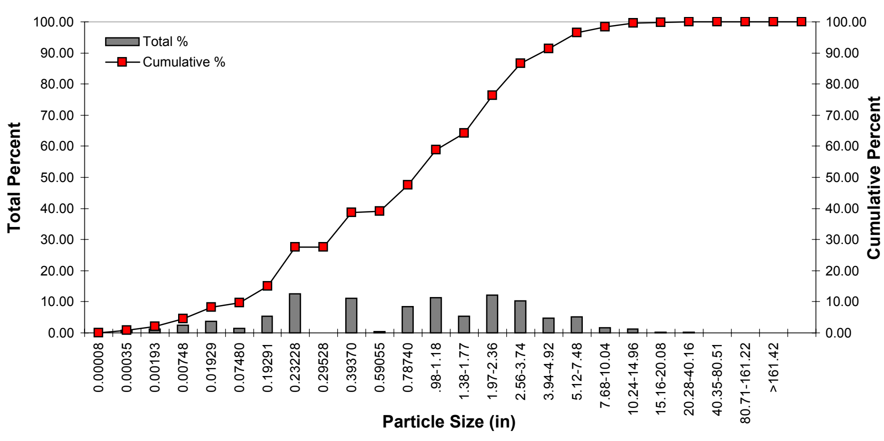
Sub-pavement

cl	0	**P**	21
si	1	**.39in**	15
vfs	1	**.59in**	14
fs	3	**.79in**	2
ms	10	**1.18in**	0
cs	10	**1.57in**	0
vcs	23	**1.97in**	0
		Bdr.	0

Particle Sizes (in)

	Pebble Counts	
D10	0.05	in
D50	0.85	in
D90	4.04	in

Substrate Particle Size Distribution Based on Pebble Counts



Appendix C

TRACTIVE FORCE ANALYSIS

Recurrence Interval Q Total (cfs)	W.S. Elev (ft)	Max Chl Dpth (ft)	Slope (ft/ft)	Tractive Force (kg/m2)	Incipient Diameter (cm)	Incipient Diameter (mm)	Incipient Diameter (in)	USCS Soil Classification
10	47.18	0.89	0.0025	0.68	0.68	6.78	0.27	fine gravel
20	47.47	1.18	0.0025	0.90	0.90	8.99	0.35	fine gravel
30	47.70	1.41	0.0025	1.07	1.07	10.74	0.42	fine gravel
40	47.90	1.61	0.0025	1.23	1.23	12.27	0.48	fine gravel
50	48.07	1.78	0.0025	1.36	1.36	13.56	0.53	fine gravel
60	48.22	1.93	0.0025	1.47	1.47	14.71	0.58	fine gravel
70	48.36	2.07	0.0025	1.58	1.58	15.77	0.62	fine gravel
80	48.50	2.21	0.0025	1.68	1.68	16.84	0.66	fine gravel
90	48.63	2.34	0.0025	1.78	1.78	17.83	0.70	fine gravel
100	48.75	2.46	0.0025	1.87	1.87	18.75	0.74	fine gravel
110	48.86	2.57	0.0025	1.96	1.96	19.58	0.77	coarse gravel
120	48.96	2.67	0.0025	2.03	2.03	20.35	0.80	coarse gravel
130	49.06	2.77	0.0025	2.11	2.11	21.11	0.83	coarse gravel
140	49.15	2.86	0.0025	2.18	2.18	21.79	0.86	coarse gravel
150	49.23	2.94	0.0025	2.24	2.24	22.40	0.88	coarse gravel
160	49.31	3.02	0.0025	2.30	2.30	23.01	0.91	coarse gravel
170	49.39	3.10	0.0025	2.36	2.36	23.62	0.93	coarse gravel
180	49.47	3.18	0.0025	2.42	2.42	24.23	0.95	coarse gravel
190	49.54	3.25	0.0025	2.48	2.48	24.77	0.98	coarse gravel
200	49.61	3.32	0.0025	2.53	2.53	25.30	1.00	coarse gravel
210	49.68	3.39	0.0025	2.58	2.58	25.83	1.02	coarse gravel
220	49.74	3.45	0.0025	2.63	2.63	26.29	1.04	coarse gravel
230	49.81	3.52	0.0025	2.68	2.68	26.82	1.06	coarse gravel
240	49.87	3.58	0.0025	2.73	2.73	27.28	1.07	coarse gravel
250	49.94	3.65	0.0025	2.78	2.78	27.81	1.10	coarse gravel
260	49.99	3.70	0.0025	2.82	2.82	28.19	1.11	coarse gravel
270	50.05	3.76	0.0025	2.87	2.87	28.65	1.13	coarse gravel
280	50.11	3.82	0.0025	2.91	2.91	29.11	1.15	coarse gravel
290	50.17	3.88	0.0025	2.96	2.96	29.57	1.16	coarse gravel
300	50.22	3.93	0.0025	2.99	2.99	29.95	1.18	coarse gravel

Table A – Tractive Force Analysis for Reach PS-2

Recurrence Interval Q Total (cfs)	W.S. Elev (ft)	Max Chl Dpth (ft)	Slope (ft/ft)	Tractive Force (kg/m2)	Incipient Diameter (cm)	Incipient Diameter (mm)	Incipient Diameter (in)	USCS Soil Classification
10	52.64	0.68	0.0102	2.11	2.11	21.14	0.83	coarse gravel
20	52.81	0.85	0.0102	2.64	2.64	26.43	1.04	coarse gravel
30	52.95	0.99	0.0102	3.08	3.08	30.78	1.21	coarse gravel
40	53.07	1.10	0.0102	3.42	3.42	34.20	1.35	coarse gravel
50	53.17	1.21	0.0102	3.76	3.76	37.62	1.48	coarse gravel
60	53.27	1.31	0.0102	4.07	4.07	40.73	1.60	coarse gravel
70	53.35	1.39	0.0102	4.32	4.32	43.21	1.70	coarse gravel
80	53.43	1.47	0.0102	4.57	4.57	45.70	1.80	coarse gravel
90	53.51	1.54	0.0102	4.79	4.79	47.88	1.88	coarse gravel
100	53.58	1.62	0.0102	5.04	5.04	50.37	1.98	coarse gravel
110	53.65	1.69	0.0102	5.25	5.25	52.54	2.07	coarse gravel
120	53.72	1.75	0.0102	5.44	5.44	54.41	2.14	coarse gravel
130	53.78	1.82	0.0102	5.66	5.66	56.58	2.23	coarse gravel
140	53.84	1.88	0.0102	5.84	5.84	58.45	2.30	coarse gravel
150	53.90	1.94	0.0102	6.03	6.03	60.31	2.37	coarse gravel
160	53.96	2.00	0.0102	6.22	6.22	62.18	2.45	coarse gravel
170	54.02	2.06	0.0102	6.40	6.40	64.04	2.52	coarse gravel
180	54.08	2.11	0.0102	6.56	6.56	65.60	2.58	coarse gravel
190	54.13	2.17	0.0102	6.75	6.75	67.46	2.66	coarse gravel
200	54.19	2.22	0.0102	6.90	6.90	69.02	2.72	coarse gravel
210	54.24	2.28	0.0102	7.09	7.09	70.88	2.79	coarse gravel
220	54.29	2.33	0.0102	7.24	7.24	72.44	2.85	coarse gravel
230	54.34	2.38	0.0102	7.40	7.40	73.99	2.91	coarse gravel
240	54.39	2.43	0.0102	7.55	7.55	75.55	2.97	cobbles
250	54.44	2.48	0.0102	7.71	7.71	77.10	3.04	cobbles
260	54.49	2.52	0.0102	7.83	7.83	78.35	3.08	cobbles
270	54.54	2.57	0.0102	7.99	7.99	79.90	3.15	cobbles
280	54.58	2.62	0.0102	8.15	8.15	81.45	3.21	cobbles
290	54.63	2.67	0.0102	8.30	8.30	83.01	3.27	cobbles
300	54.68	2.71	0.0102	8.43	8.43	84.25	3.32	cobbles

Table B – Tractive Force Analysis for Reach PS-4

Recurrence Interval Q Total (cfs)	W.S. Elev (ft)	Max Chl Dpth (ft)	Slope (ft/ft)	Tractive Force (kg/m2)	Incipient Diameter (cm)	Incipient Diameter (mm)	Incipient Diameter (in)	USCS Soil Classification
10	98.02	1.10	0.0059	1.98	1.98	19.78	0.78	coarse gravel
20	98.42	1.50	0.0059	2.70	2.70	26.97	1.06	coarse gravel
30	98.62	1.71	0.0059	3.08	3.08	30.75	1.21	coarse gravel
40	98.79	1.87	0.0059	3.36	3.36	33.63	1.32	coarse gravel
50	98.94	2.02	0.0059	3.63	3.63	36.33	1.43	coarse gravel
60	99.13	2.22	0.0059	3.99	3.99	39.92	1.57	coarse gravel
70	99.25	2.33	0.0059	4.19	4.19	41.90	1.65	coarse gravel
80	99.35	2.44	0.0059	4.39	4.39	43.88	1.73	coarse gravel
90	99.45	2.54	0.0059	4.57	4.57	45.68	1.80	coarse gravel
100	99.56	2.65	0.0059	4.77	4.77	47.66	1.88	coarse gravel
110	99.67	2.75	0.0059	4.95	4.95	49.45	1.95	coarse gravel
120	99.77	2.86	0.0059	5.14	5.14	51.43	2.02	coarse gravel
130	99.85	2.94	0.0059	5.29	5.29	52.87	2.08	coarse gravel
140	99.93	3.01	0.0059	5.41	5.41	54.13	2.13	coarse gravel
150	100.01	3.09	0.0059	5.56	5.56	55.57	2.19	coarse gravel
160	100.07	3.16	0.0059	5.68	5.68	56.83	2.24	coarse gravel
170	100.14	3.22	0.0059	5.79	5.79	57.91	2.28	coarse gravel
180	100.20	3.28	0.0059	5.90	5.90	58.98	2.32	coarse gravel
190	100.26	3.34	0.0059	6.01	6.01	60.06	2.36	coarse gravel
200	100.32	3.40	0.0059	6.11	6.11	61.14	2.41	coarse gravel
210	100.38	3.46	0.0059	6.22	6.22	62.22	2.45	coarse gravel
220	100.43	3.52	0.0059	6.33	6.33	63.30	2.49	coarse gravel
230	100.49	3.57	0.0059	6.42	6.42	64.20	2.53	coarse gravel
240	100.55	3.63	0.0059	6.53	6.53	65.28	2.57	coarse gravel
250	100.60	3.69	0.0059	6.64	6.64	66.36	2.61	coarse gravel
260	100.66	3.74	0.0059	6.73	6.73	67.26	2.65	coarse gravel
270	100.71	3.79	0.0059	6.82	6.82	68.16	2.68	coarse gravel
280	100.76	3.85	0.0059	6.92	6.92	69.24	2.73	coarse gravel
290	100.82	3.90	0.0059	7.01	7.01	70.13	2.76	coarse gravel
300	100.87	3.95	0.0059	7.10	7.10	71.03	2.80	coarse gravel

Table C – Tractive Force Analysis for Reach PS-6/PS-7

Recurrence Interval Q Total (cfs)	W.S. Elev (ft)	Max Chl Dpth (ft)	Slope (ft/ft)	Tractive Force (kg/m2)	Incipient Diameter (cm)	Incipient Diameter (mm)	Incipient Diameter (in)	USCS Soil Classification
10	59.44	1.36	0.0026	1.08	1.08	10.78	0.42	fine gravel
20	59.80	1.72	0.0026	1.36	1.36	13.63	0.54	fine gravel
30	60.02	1.94	0.0026	1.54	1.54	15.37	0.61	fine gravel
40	60.18	2.10	0.0026	1.66	1.66	16.64	0.66	fine gravel
50	60.33	2.25	0.0026	1.78	1.78	17.83	0.70	fine gravel
60	60.47	2.39	0.0026	1.89	1.89	18.94	0.75	fine gravel
70	60.61	2.53	0.0026	2.00	2.00	20.05	0.79	coarse gravel
80	60.73	2.65	0.0026	2.10	2.10	21.00	0.83	coarse gravel
90	60.85	2.77	0.0026	2.20	2.20	21.95	0.86	coarse gravel
100	60.97	2.89	0.0026	2.29	2.29	22.90	0.90	coarse gravel
110	61.08	3.00	0.0026	2.38	2.38	23.77	0.94	coarse gravel
120	61.19	3.11	0.0026	2.46	2.46	24.65	0.97	coarse gravel
130	61.29	3.21	0.0026	2.54	2.54	25.44	1.00	coarse gravel
140	61.40	3.32	0.0026	2.63	2.63	26.31	1.04	coarse gravel
150	61.50	3.42	0.0026	2.71	2.71	27.10	1.07	coarse gravel
160	61.60	3.52	0.0026	2.79	2.79	27.90	1.10	coarse gravel
170	61.70	3.62	0.0026	2.87	2.87	28.69	1.13	coarse gravel
180	61.79	3.71	0.0026	2.94	2.94	29.40	1.16	coarse gravel
190	61.89	3.81	0.0026	3.02	3.02	30.19	1.19	coarse gravel
200	61.98	3.90	0.0026	3.09	3.09	30.91	1.22	coarse gravel
210	62.07	3.99	0.0026	3.16	3.16	31.62	1.24	coarse gravel
220	62.16	4.08	0.0026	3.23	3.23	32.33	1.27	coarse gravel
230	62.25	4.17	0.0026	3.30	3.30	33.05	1.30	coarse gravel
240	62.33	4.25	0.0026	3.37	3.37	33.68	1.33	coarse gravel
250	62.42	4.34	0.0026	3.44	3.44	34.39	1.35	coarse gravel
260	62.51	4.43	0.0026	3.51	3.51	35.11	1.38	coarse gravel
270	62.59	4.51	0.0026	3.57	3.57	35.74	1.41	coarse gravel
280	62.67	4.59	0.0026	3.64	3.64	36.37	1.43	coarse gravel
290	62.76	4.68	0.0026	3.71	3.71	37.09	1.46	coarse gravel
300	62.84	4.76	0.0026	3.77	3.77	37.72	1.49	coarse gravel

Table D – Tractive Force Analysis for Reach PST1-2

Recurrence Interval Q Total (cfs)	W.S. Elev (ft)	Max Chl Dpth (ft)	Slope (ft/ft)	Tractive Force (kg/m2)	Incipient Diameter (cm)	Incipient Diameter (mm)	Incipient Diameter (in)	USCS Soil Classification
10	57.63	1.21	0.0095	3.50	3.50	35.04	1.38	coarse gravel
20	58.02	1.60	0.0095	4.63	4.63	46.33	1.82	coarse gravel
30	58.34	1.92	0.0095	5.56	5.56	55.60	2.19	coarse gravel
40	58.62	2.20	0.0095	6.37	6.37	63.70	2.51	coarse gravel
50	58.88	2.46	0.0095	7.12	7.12	71.23	2.80	coarse gravel
60	59.40	2.98	0.0095	8.63	8.63	86.29	3.40	cobbles
70	59.57	3.15	0.0095	9.12	9.12	91.21	3.59	cobbles
80	59.70	3.28	0.0095	9.50	9.50	94.98	3.74	cobbles
90	59.89	3.47	0.0095	10.05	10.05	100.48	3.96	cobbles
100	60.01	3.59	0.0095	10.40	10.40	103.95	4.09	cobbles
110	60.08	3.66	0.0095	10.60	10.60	105.98	4.17	cobbles
120	60.15	3.73	0.0095	10.80	10.80	108.01	4.25	cobbles
130	60.21	3.79	0.0095	10.97	10.97	109.74	4.32	cobbles
140	60.27	3.85	0.0095	11.15	11.15	111.48	4.39	cobbles
150	60.33	3.91	0.0095	11.32	11.32	113.22	4.46	cobbles
160	60.39	3.97	0.0095	11.50	11.50	114.96	4.53	cobbles
170	60.44	4.02	0.0095	11.64	11.64	116.40	4.58	cobbles
180	60.50	4.08	0.0095	11.81	11.81	118.14	4.65	cobbles
190	60.56	4.14	0.0095	11.99	11.99	119.88	4.72	cobbles
200	60.61	4.19	0.0095	12.13	12.13	121.33	4.78	cobbles
210	60.66	4.24	0.0095	12.28	12.28	122.77	4.83	cobbles
220	60.71	4.29	0.0095	12.42	12.42	124.22	4.89	cobbles
230	60.77	4.35	0.0095	12.60	12.60	125.96	4.96	cobbles
240	60.82	4.40	0.0095	12.74	12.74	127.41	5.02	cobbles
250	60.87	4.45	0.0095	12.89	12.89	128.85	5.07	cobbles
260	60.91	4.49	0.0095	13.00	13.00	130.01	5.12	cobbles
270	60.96	4.54	0.0095	13.15	13.15	131.46	5.18	cobbles
280	61.01	4.59	0.0095	13.29	13.29	132.91	5.23	cobbles
290	61.06	4.64	0.0095	13.44	13.44	134.36	5.29	cobbles
300	61.10	4.68	0.0095	13.55	13.55	135.51	5.34	cobbles

Table E – Tractive Force Analysis for Reach PST2-3

Recurrence Interval Q Total (cfs)	W.S. Elev (ft)	Max Chl Dpth (ft)	Slope (ft/ft)	Tractive Force (kg/m2)	Incipient Diameter (cm)	Incipient Diameter (mm)	Incipient Diameter (in)	USCS Soil Classification
10	118.75	0.64	0.0184	3.59	3.59	35.89	1.41	coarse gravel
20	119.00	0.89	0.0184	4.99	4.99	49.91	1.97	coarse gravel
30	119.16	1.05	0.0184	5.89	5.89	58.89	2.32	coarse gravel
40	119.30	1.19	0.0184	6.67	6.67	66.74	2.63	coarse gravel
50	119.41	1.30	0.0184	7.29	7.29	72.91	2.87	coarse gravel
60	119.52	1.41	0.0184	7.91	7.91	79.08	3.11	cobbles
70	119.62	1.51	0.0184	8.47	8.47	84.69	3.33	cobbles
80	119.70	1.59	0.0184	8.92	8.92	89.17	3.51	cobbles
90	119.86	1.75	0.0184	9.81	9.81	98.15	3.86	cobbles
100	119.94	1.83	0.0184	10.26	10.26	102.63	4.04	cobbles
110	120.02	1.91	0.0184	10.71	10.71	107.12	4.22	cobbles
120	120.09	1.98	0.0184	11.10	11.10	111.04	4.37	cobbles
130	120.15	2.04	0.0184	11.44	11.44	114.41	4.50	cobbles
140	120.21	2.10	0.0184	11.78	11.78	117.77	4.64	cobbles
150	120.27	2.16	0.0184	12.11	12.11	121.14	4.77	cobbles
160	120.32	2.21	0.0184	12.39	12.39	123.94	4.88	cobbles
170	120.37	2.26	0.0184	12.67	12.67	126.75	4.99	cobbles
180	120.42	2.31	0.0184	12.96	12.96	129.55	5.10	cobbles
190	120.47	2.36	0.0184	13.24	13.24	132.36	5.21	cobbles
200	120.55	2.44	0.0184	13.68	13.68	136.84	5.39	cobbles
210	120.60	2.49	0.0184	13.96	13.96	139.65	5.50	cobbles
220	120.65	2.54	0.0184	14.25	14.25	142.45	5.61	cobbles
230	120.69	2.58	0.0184	14.47	14.47	144.69	5.70	cobbles
240	120.74	2.63	0.0184	14.75	14.75	147.50	5.81	cobbles
250	120.78	2.67	0.0184	14.97	14.97	149.74	5.90	cobbles
260	120.83	2.72	0.0184	15.25	15.25	152.55	6.01	cobbles
270	120.87	2.76	0.0184	15.48	15.48	154.79	6.09	cobbles
280	120.91	2.80	0.0184	15.70	15.70	157.03	6.18	cobbles
290	120.95	2.84	0.0184	15.93	15.93	159.28	6.27	cobbles
300	121.03	2.92	0.0184	16.38	16.38	163.76	6.45	cobbles

Table F – Tractive Force Analysis for Reach PST5-4

Appendix D

RESTORATION TECHNIQUES

Numerous bioengineering methods are available to reduce bank erosion while improving channel habitat. The objectives of the restoration project (i.e., habitat improvement, infrastructure protection), scope of work, cost of bank treatment failure (i.e., what is at risk) and resources available will dictate what methods are most appropriate. Bioengineering methods for bank protection presented include simple planting and re-grading, wattles, brush matting, vegetated rip rap, root wads, vegetated cribwalls, and log deflectors. These methods allow bank erosion to be retarded and can also be used to narrow sections of channel to provide increased bed scour and the development of deeper channel pools.

The simplest methods are limited re-grading and bank planting. This simple approach is very economical, installation is not complicated, but has a lower success rate compared to more substantial and structured restoration techniques.

Wattles, brush matting and vegetated rip-rap provide increased levels of bank protection, success rates are higher than simple replanting, but construction work is slightly more complicated and in the case of vegetated rip rap some large machinery may be required. These methods are more successful than simple plantings as they provide initial bank protection to allow vegetation root structures to develop. Wattles and brush matting only require plant materials and are easily installed. These methods provide some habitat benefits, mostly through reduction in bank sediment inputs, decrease in channel width, riparian buffer and channel shading.

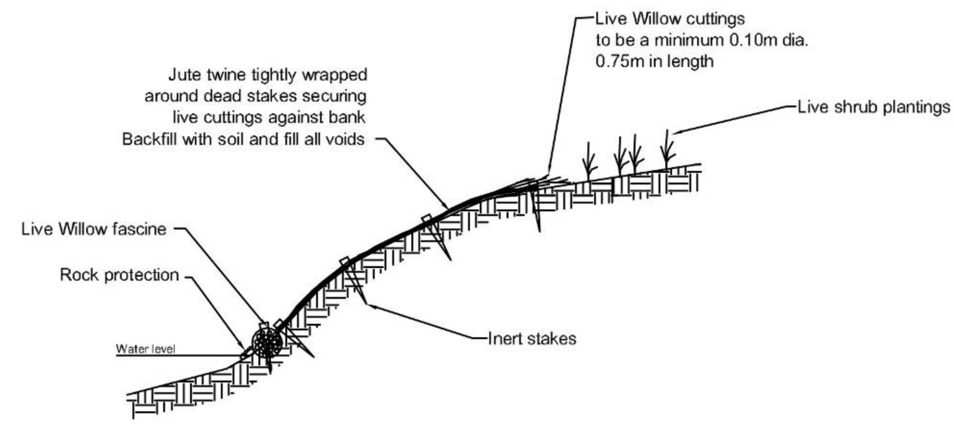
Root wads, although not bank protection features, per se, have been used as such. Generally, root wads should be used to provide channel bank habitat. As the root wad creates local flow acceleration and redirection they can exacerbate local bank erosion if not installed correctly. Generally, they need to be used in clusters to provide bank protection and may require additional stone work and riparian planting to be effective. As root wads need to be installed into the bank, some heavy equipment may be required. These features are best used to protect abandoned channels when backfilling will be required and little excavation is necessary. Cribwalls and log deflectors require a similar level of effort, compared to root wads, but provide better bank erosion control.

Vegetated crib walls and un-vegetated log deflectors are more complicated structures to install, but they provide substantial bank protection and in the case of the log deflectors train the flow to redirect erosive forces. These structures generally require heavy equipment to install and a skilled operator, and as such, have higher per unit costs and may not be appropriate for volunteer works. The vegetated crib wall is a gravity structure and provides substantial bank protection. Minor undercutting of the cribwall does not overly effect the protection or structural integrity provided, as the support logs act as a cantilever, furthermore the undercutting provides additional habitat. Log deflectors are also built into the bank and therefore have similar performance. These features are less costly than cribwalls, as they are smaller, and may provide additional habitat benefits as they create diverse bank geometry. This in turn contributes variability to channel habitat. Some care in the placement of these structures is needed as they redirect flows and can create additional, and in many cases unexpected, erosion issues. Aggressive bank plantings should accompany these structures to reduce the chance of undermining or out flanking.

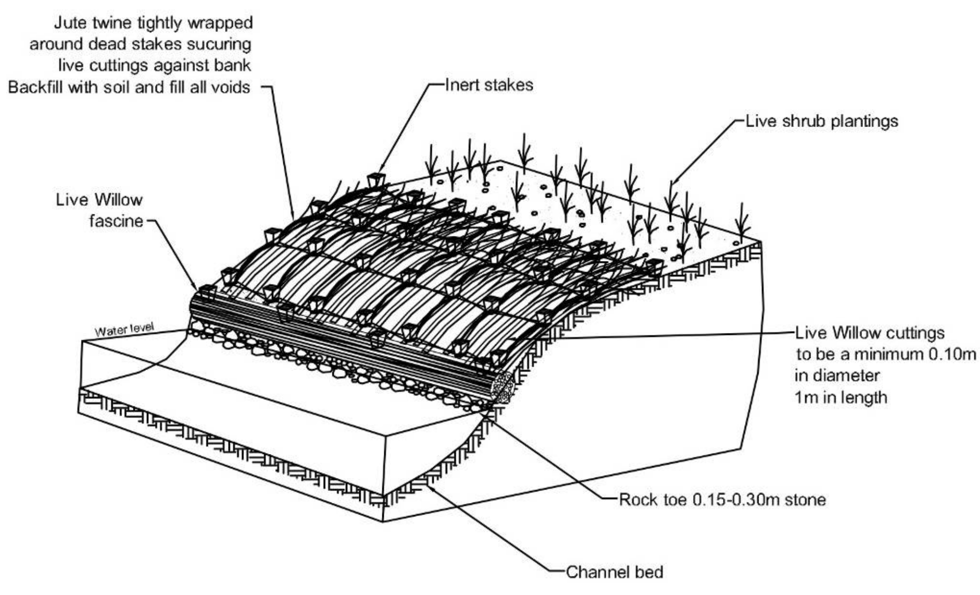
In many cases, entrenchment will need to be addressed along with the problem of bank erosion. The cumulative erosive forces on channel bed and bank are reduced by improving connection to the floodplain. Along with re-grading of banks, instream structures such as riffles, cross-vanes and cascades will need to be established. Many of these structures can be installed with physical labour; however, machinery may be needed depending on the size and amount of material required.

BRUSH MATTRESS TREATMENT TYPICAL DETAIL

NTS



Cross-section view

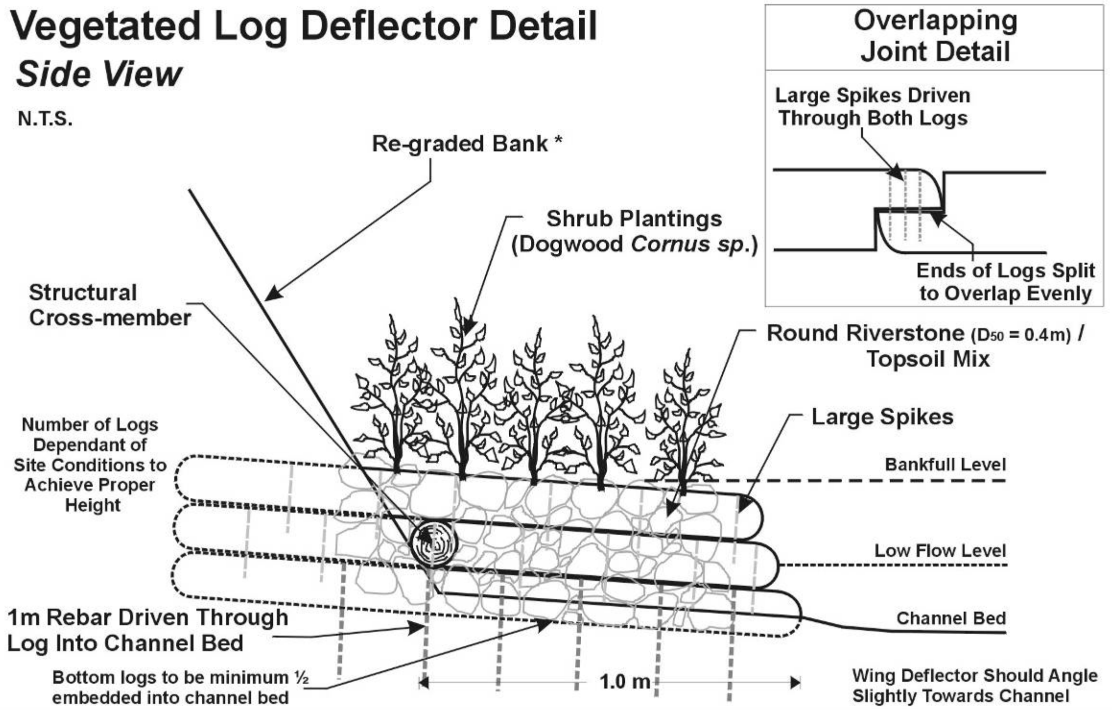


Isometric view

Vegetated Log Deflector Detail

Side View

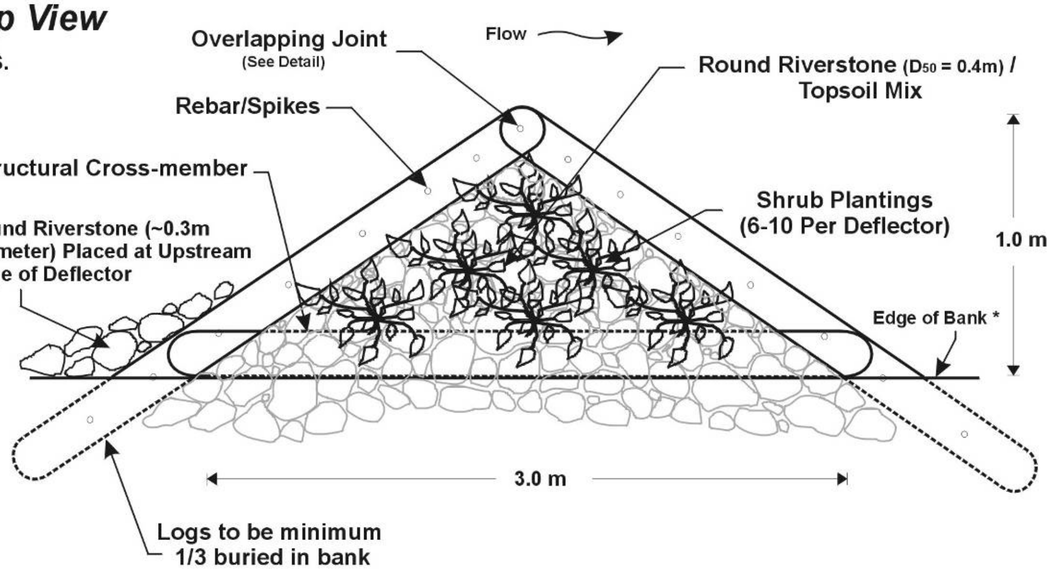
N.T.S.



Vegetated Log Deflector Detail

Top View

N.T.S.

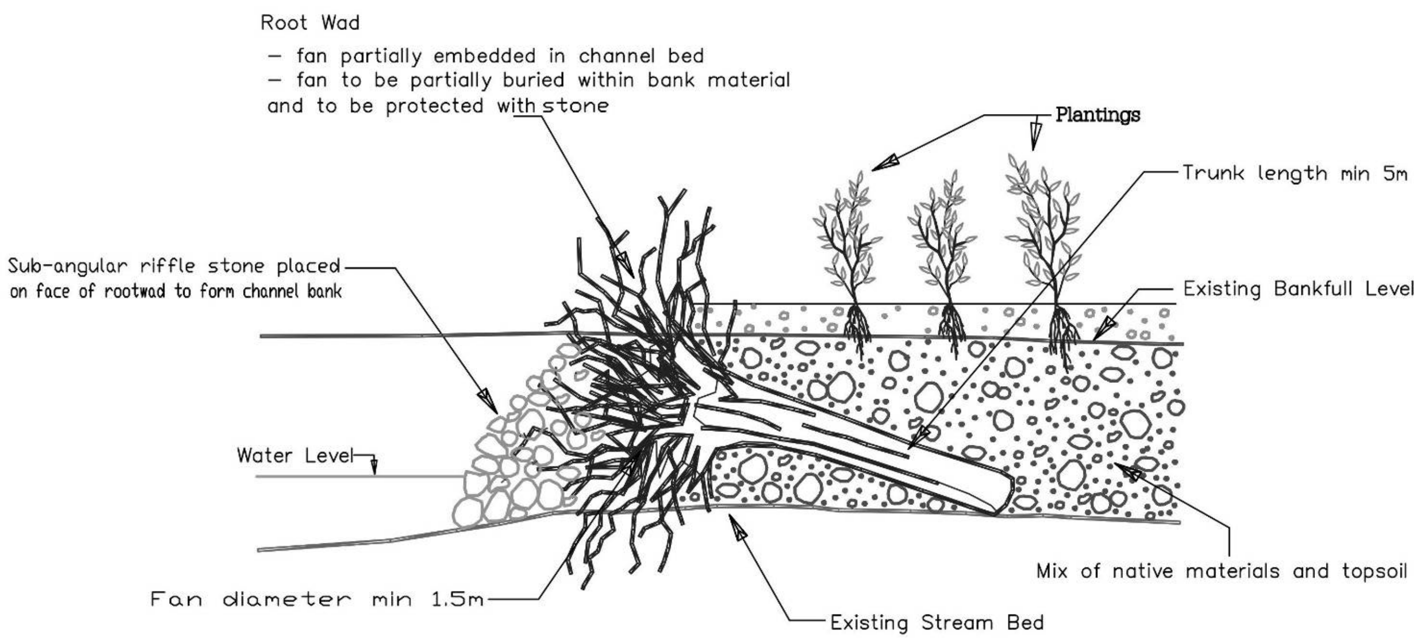


Logs should be Cedar and approximately 3 - 4m in length and 0.2-0.4m in diameter

* May be Constructed in Conjunction with Vegetated Cribwall or Vegetated Buttress

ROOTWAD TREATMENT TYPICAL DETAIL

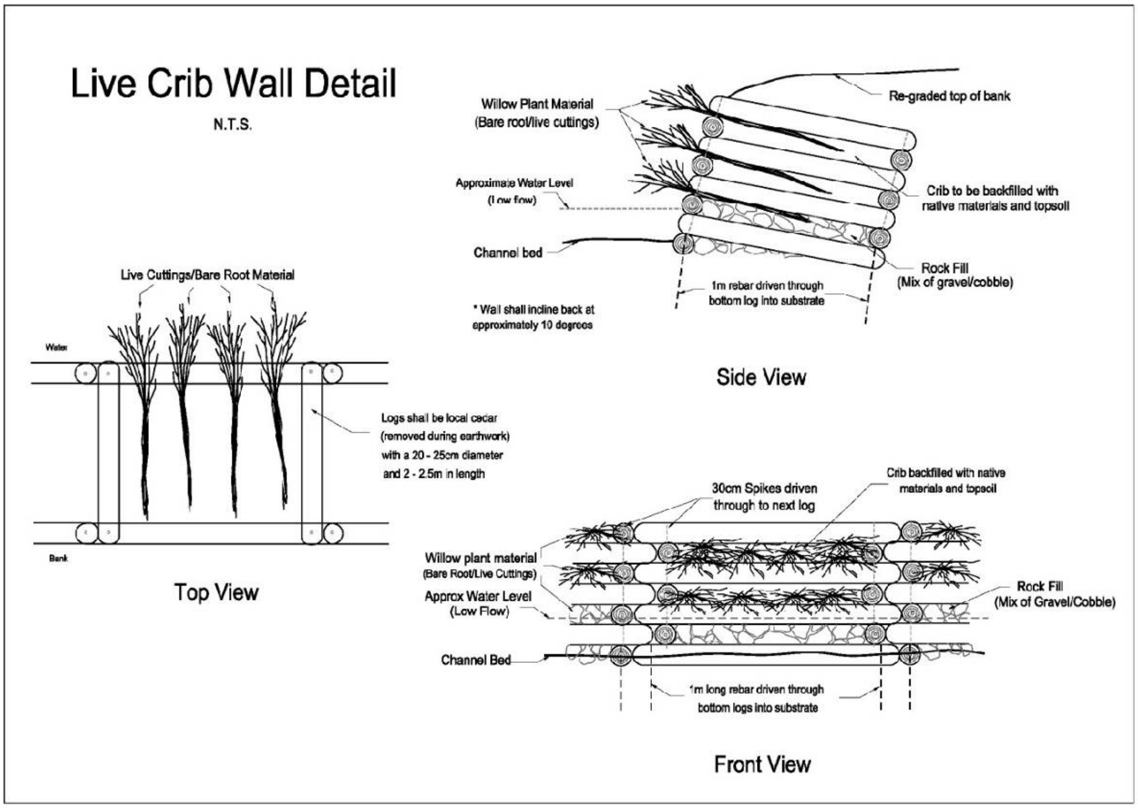
N.T.S.



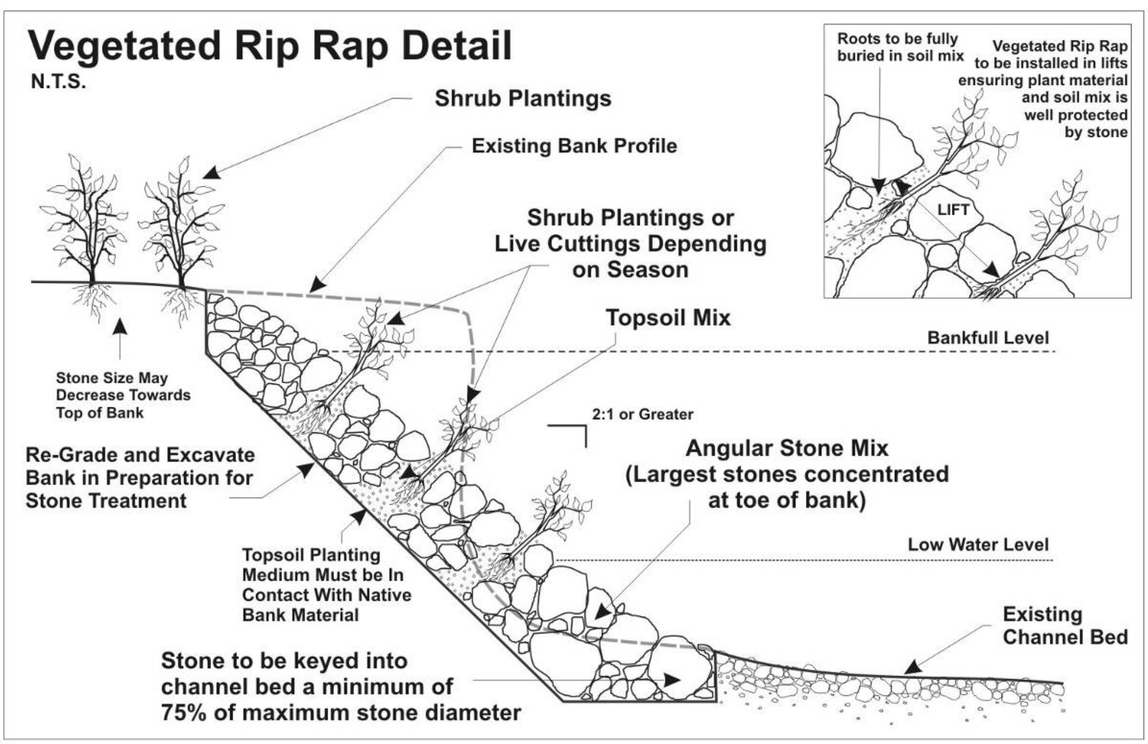
– Existing stream to be filled at minimum to existing bankfull level with native materials and top dressed with topsoil for planting.

– Root wad to be buried within existing channel with roots towards new channel.

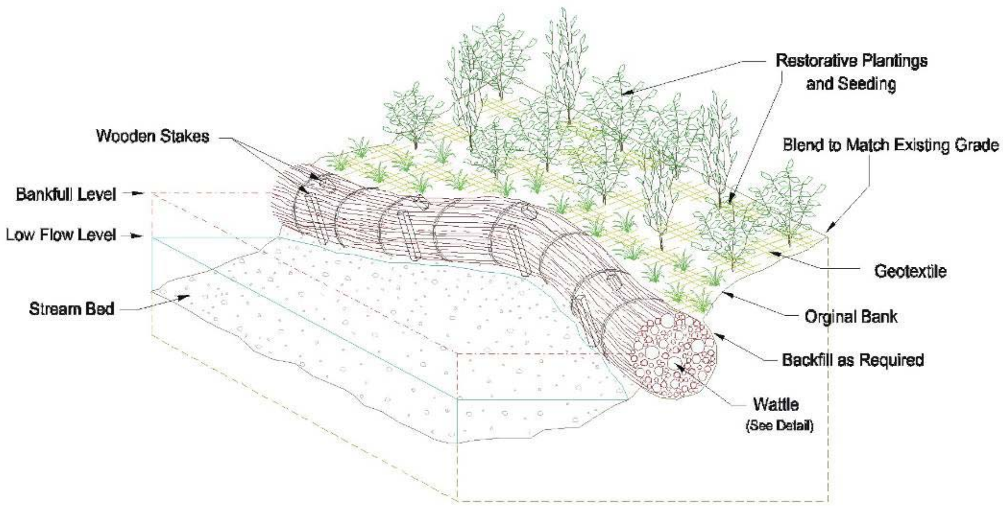
Species should be hardwood or slow decaying coniferous (eg. Hemlock). Willow and Poplar to be avoided



Live Crib Wall Detail
N.T.S.
Willow Plant Material
(Bare root/live cuttings)
Re-graded top of bank
Approximate Water Level
(Low flow)
Crib to be backfilled with
native materials and topsoil
Channel bed
Rock Fill
(Mix of gravel/cobble)
1m rebar driven through
bottom log into substrate
* Wall shall incline back at
approximately 10 degrees
Side View
Live Cuttings/Bare Root Material
Water
Logs shall be local cedar
(removed during earthwork)
with a 20 - 25cm diameter
and 2 - 2.5m in length
Bank
Top View
30cm Spikes driven
through to next log
Crib backfilled with native
materials and topsoil
Willow plant material
(Bare Root/Live Cuttings)
Approx Water Level
(Low Flow)
Rock Fill
(Mix of Gravel/Cobble)
Channel Bed
1m long rebar driven through
bottom logs into substrate
Front View



Vegetated Rip Rap Detail
N.T.S.
Shrub Plantings
Existing Bank Profile
Roots to be fully
buried in soil mix
Vegetated Rip Rap
to be installed in lifts
ensuring plant material
and soil mix is
well protected
by stone
LIFT
Shrub Plantings or
Live Cuttings Depending
on Season
Topsoil Mix
Bankfull Level
Stone Size May
Decrease Towards
Top of Bank
2:1 or Greater
Re-Grade and Excavate
Bank in Preparation for
Stone Treatment
Angular Stone Mix
(Largest stones concentrated
at toe of bank)
Low Water Level
Topsoil Planting
Medium Must be In
Contact With Native
Bank Material
Existing
Channel Bed
Stone to be keyed into
channel bed a minimum of
75% of maximum stone diameter



Wattle Installation

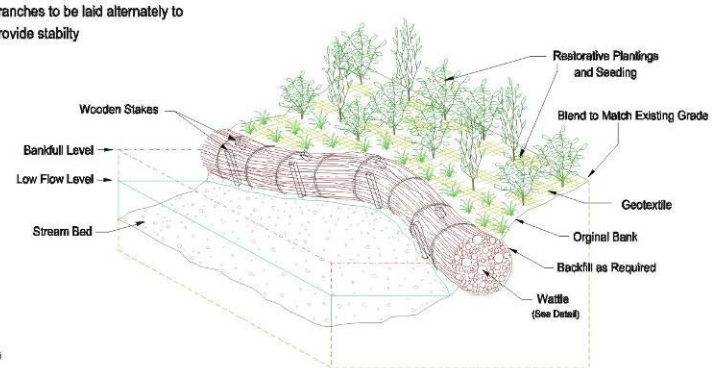
(Isometric View)

(N.T.S.)

- approx. 20 - 25 cm diameter
- tie bundle every 30 - 45 cm
- bundle to be constructed with branches of live mixed willow species
- branches to be laid alternately to provide stabilty

Wattle Detail

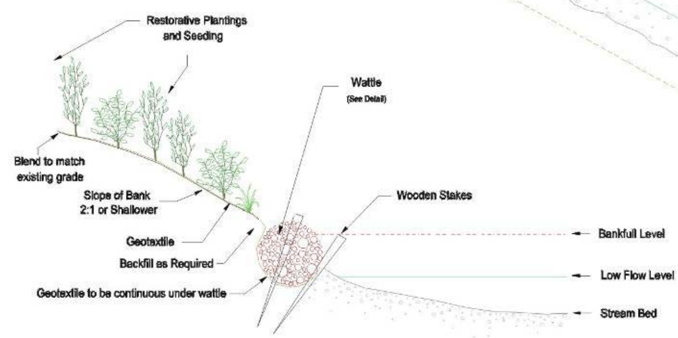
(N.T.S.)



Wattle Installation

(Isometric View)

(N.T.S.)



Wattle Installation

(Section View)

(N.T.S.)

Appendix E

GLOSSARY OF GEOMORPHIC TERMS

<u>**Glossary of Geomorphic Terms**</u>

Aggradation

The process by which a stream deposits sediment

Average Bankfull Depth

This is the average vertical distance between the channel bed and the estimated water surface elevation required to completely fill the channel to a point above which water would enter the floodplain or intersect a terrace or hillslope

Average Bankfull Width

This is the average channel width at bankfull discharge

Average Bankfull Velocity

Estimates of bankfull velocity are used to determine whether substrate is being entrained under bankfull flow conditions

Bank Critical Shear

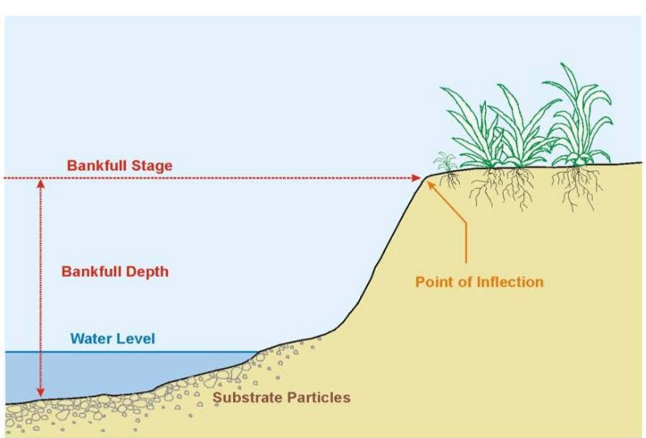
The minimum force required to liberate materials from the banks of the channel

Bank Materials

This refers to the bank composition and provides an indication of the degree to which the banks are resistant to erosive forces

Bankfull

Bankfull is defined as the point at which the channel is completely full just prior to flows over- topping the banks and occupying the floodplain. The *Bankfull Stage* is typically the point at which, over time, flows within the channel can do the most work on the channel with the least amount of water in the channel (e.g. erosion, deposition, sediment transport.)



Bankfull Discharge

Conceptually this is the flow that fills the channel just prior to spilling onto the floodplain. In a watercourse that is in equilibrium with respect to its controls and modifying influences, bankfull discharge is the same as the dominant discharge. Statistically, in rural watercourses, bankfull discharge occurs once every 1.6 years. In urban settings, the frequency of bankfull discharge increases and may occur 2 or more times per year. Bankfull flow stage is typically defined by field indicators and in most instances is actually located below the top-of-bank.

Bankfull Gradient

This is the key to understanding channel form and process as it represents the water surface gradient during bankfull flow and can be directly related to relationships between channel defining flows and the form and function of the channel

Bed Condition

Refers to the substrate and stability of the channel bed and provides an indication whether the stream bed is cohesive, non cohesive, or bedrock controlled

Bed Material D-50

This value defines the median diameter of the substrate present in the channel

Bed Material D-84

This value indicates the diameter at which 84% of the substrate particles falls at or below

Critical Discharge

The minimum amount of discharge required to erode the channel bed and banks

Critical Depth

This value indicates the minimum depth of water at which channel erosion will begin to occur

Critical Velocity

This represents the minimum velocity required to entrain channel sediments

Degradation

The process by which a stream erodes sediment

Fine Cohesive Sediment

Cohesive sediment means clay (fine grained soil), or soil with a high clay content, which has cohesive strength. Cohesive soil does not crumble, can be excavated with vertical side slopes, and is plastic when moist. Cohesive soil is hard to break up when dry, and exhibits significant cohesion when submerged. Cohesive soils include clayey silt, sandy clay,silty clay, clay and organic clay.

Flow Competence

The ability to move a particle of a given size

Gradient

The slope of a surface as determined by the quotient of rise over run

"In Adjustment"

According to the SWM Planning & Design Manual by the Ministry of the Environment (2003), "channel morphology is not within the range of variance and evidence of instability is wide spread"

"In Regime"

According to the SWM Planning & Design Manual by the Ministry of the Environment (2003), "the channel morphology is within a range of variance set for streams of similar hydrographic characteristics – evidence of instability is isolated or associated with normal river meander propagation processes".

"In Transition/Transitional"

According to the SWM Planning & Design Manual by the Ministry of the Environment (2003), "channel morphology is within the range of variance for streams of similar hydrographic characteristics but the evidence of instability is frequent"

Manning's n

This value represents the estimated roughness coefficient determined for the channel bed and is used to characterize energy losses as water flows down a stream

Migration Rate

Quantifies the rate that a meander bend of a stream moves across its valley and are used to help predict future shifts of the channel

Permissible Velocity

The highest velocity that water may be carried through a channel

Reach

A longitudinal section of a watercourse that displays fairly consistent physical characteristics, such as substrate materials, channel dimensions, and gradient. The controls and modifiers of channel form are similar along the reach

Stream Order

A stream classification system based on the number of upstream branches or tributaries possessed by a particular drainage network. Unbranched streams are classified as first order. When two first order streams confluence, the resultant stream becomes a second order. Whenever two streams of equal order (n) confluence, the resultant downstream channel is given a number of (n + 1). If a lower order tributary joins the main channel, the stream order does not change. The objective of the classification system is to be able to describe a link in the drainage network anywhere in the world in an unambiguous manner, and also to provide an ordering system that can readily provide an indication of discharge from a network.

Stream Power

This is a calculated quantity that represents the rate of energy that is available to do work (i.e., transport sediment) per unit length along a channel

Tractive Force on Bed

Refers to the force on the bed of the channel created by channel flows

Tractive Force on Banks

Refers to the force on the banks of the channel created by channel flows